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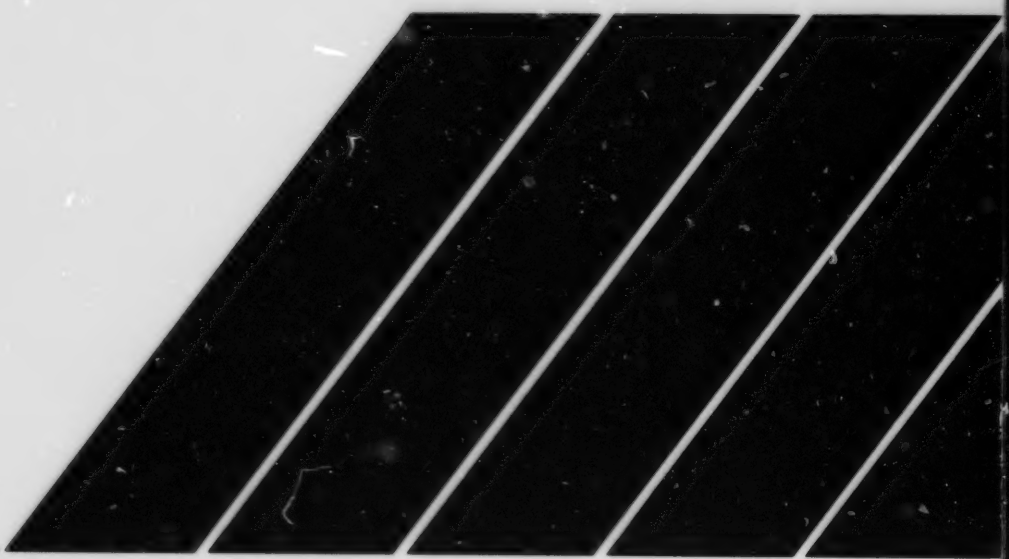
DI-METHYL ETHER AS AN IGNITION ASSISTANCE SOURCE FOR A HEAVY-DUTY METHANOL ENGINE



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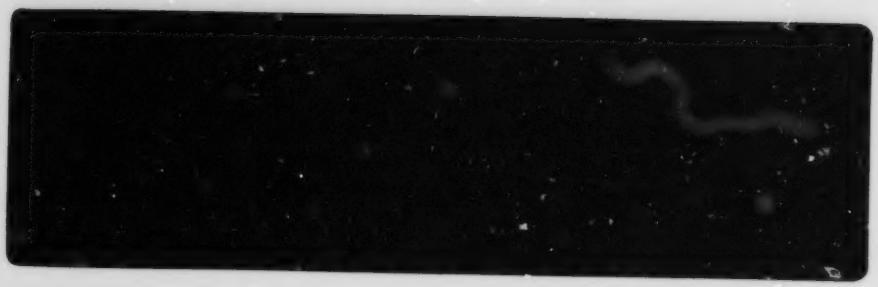

DI-METHYL ETHER AS AN IGNITION ASSISTANCE SOURCE FOR A HEAVY-DUTY METHANOL ENGINE

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ORTECH International, May, 1990.

RÉSUMÉ

En novembre 1988, Énergie, Mines et Ressources Canada a fait une demande de propositions quant à des projets qui seraient menés dans le cadre du Programme d'aide à la recherche relative aux carburants de transport (ARCT). Ce programme avait pour but d'encourager la recherche à haut risque dans le domaine des carburants de rechange. A l'époque, la société SYPHER:MUELLER International gérait le projet Méthanol pour moteurs puissants (projet MPMP) pour le compte d'Énergie, Mines et Ressources Canada. Ce projet comportait la mise à l'essai en vrai grandeur du méthanol comme carburant d'autobus et de camions lourds. L'un des principaux problèmes que le projet MPMP a mis en évidence avait trait à la fiabilité douteuse des méthodes requises pour amorcer l'allumage en vue de la combustion du méthanol dans les moteurs à allumage par compression. On a utilisé des bougies de préchauffage et des additifs, selon la marque du moteur, pour améliorer l'allumage dans les véhicules utilisés aux fins du projet. Plusieurs autres dispositifs avaient été utilisés à cette fin dans les moteurs d'autres fabricants, notamment les systèmes d'allumage par étincelle utilisés dans des moteurs à essence et la préinjection du carburant diesel. Aucune de ces méthodes n'a donné le degré de fiabilité requis pour permettre aux moteurs alimentés au méthanol de faire une bonne concurrence aux moteurs diesel. L'occasion s'est présentée d'examiner plus en détail la question fondamentale de l'injection du méthanol. La SYPHER:MUELLER International a proposé un projet visant à examiner la production de diméthyléther (DME) et à mélanger ce produit à l'air d'admission d'un moteur alimenté au méthanol. Le DME s'allume spontanément aux températures produites durant la course de compression d'un moteur, ce qui constitue une bonne source de préinjection en vue de l'allumage de la charge principale de carburant méthanol. Le DME est obtenu par un processus relativement simple de dissociation catalytique du méthanol.

Le projet avait pour but de construire un convertisseur catalytique qui produirait du DME et de l'utiliser pour faire fonctionner un moteur de recherche monocylindrique à allumage par compression, qui était alimenté à 100 pour 100 au méthanol. Divers essais étaient prévus afin de déterminer la quantité de DME requise pour l'allumage stable à différents paramètres de fonctionnement du moteur (vitesse et charge, puissance et couple, consommation de carburant et autres).

La SYPHER:MUELLER International a retenu les services de la société ORTECH International de Mississauga quant à la conception et à la construction d'un générateur de DME, et à la mise à

l'essai du moteur.

L'étude permet de conclure que l'utilisation du DME pour améliorer l'allumage par compression du méthanol pour injecté directement est une méthode viable qui produit des effets très positifs sur le rendement et les émissions du moteur diesel lourd selon la gamme de vitesses et de charges pour lesquelles il est conçu.

Le tableau 6 présente la quantité de DME requise pour assurer le fonctionnement stable du moteur utilisé dans le cadre de l'étude.

Tableau 6. Pourcentage de carburant décomposé

Vitesse/charge (% tr min)	% de méthanol (masse)	% de DME (masse)
800/0	41	59
1300/2	76	24
1300/25	90	10
1300/50	98	2
1300/75	98	2
1300/100	99	1
1900/2	81	19
1900/25	84	16
1900/50	98	2
1900/75	99	1
1900/100	99	1

Les émissions de CO et de NO_x ont augmenté légèrement, tandis que les émissions totales d'hydrocarbures ont baissé radicalement, par comparaison avec celles d'un moteur dans lequel l'allumage est assuré par une bougie de préchauffage. On obtient la réduction d'émissions la plus remarquable lorsque la charge est faible. Les résultats sont donnés à l'annexe 3.

Ces résultats confirment l'utilité du DME pour le fonctionnement d'un moteur diesel lourd alimenté au méthanol. La prochaine étape logique consiste à utiliser ces données pour concevoir un convertisseur catalytique capable de produire la quantité de DME requise directement à partir du méthanol et à le mettre à l'essai dans un moteur de série multicylindrique. Une grande partie des travaux de base sur le catalyseur ont été effectués par Michael Karpuk et Scott Cowley. Il faudrait aussi mettre au point et construire un système de commande pour réglementer la production de DME et son admission dans le moteur.

I INTRODUCTION

A. BACKGROUND

In November, 1988, Energy, Mines and Resources Canada issued a request for proposals for projects to be carried out as part of the Transportation Energy Research Assistance (TERA) program. The intention of the program was to encourage high-risk research work in the area of alternative fuels for transportation purposes. At the time SYPHER:MUELLER International was managing the Methanol in Large Engines (MILE) project for Energy, Mines and Resources. This project was a large scale field trial of methanol as a fuel for heavy-duty trucks and buses. One of the primary concerns which had emerged from MILE was the questionable reliability of the ignition assistance methods necessary to burn methanol in compression ignition engines. Project vehicles used glow plugs and ignition enhancement additives, according to make of engine fitted. Several other devices had been used for this purpose in other manufacturers engines, including gasoline engine type spark ignition systems, and pilot injection of diesel fuel. None of them had achieved standards of reliability necessary for methanol engines to compete effectively against diesel power. There was an opportunity for more research into the fundamental question of methanol fuel ignition.
SYPHER:MUELLER International proposed a project to investigate the generation and introduction of di-methyl ether (DME) into the inlet air stream of a methanol engine. DME will spontaneously ignite at temperatures generated during the engine compression stroke, and therefore can form an effective pilot ignition source to fire the main charge of methanol fuel. DME may be generated from methanol by a relatively simple catalytic dissociation process.

The intention of the project was to construct a catalytic reactor device to generate di-methyl ether and use it to operate a single cylinder compression-ignition research engine on 100% methanol fuel. Various tests were to be performed to determine the amount of DME required for stable ignition at varying speeds and loads, power and torque output, fuel consumption, and other engine operating parameters.

SYPHER:MUELLER International engaged ORTECH International of Mississauga as a sub-contractor to design and construct the DME generator and carry out engine testing.

During the early stages of the project other researchers in New Zealand announced that they had successfully built a catalytic reactor to generate DME on-board a working vehicle. The reactor had been installed and tested on a small pickup truck. This information led to a decision in June 1989 to alter the emphasis of the project work away from construction of a catalytic reactor, to a more thorough investigation of engine operation when using DME, particularly regarding exhaust emissions output. DME was supplied in pressurized gas cylinders, and introduced into the engine through a metering valve.

B. OBJECTIVES

The original objectives of the project were as follows:

1. Configure and instrument a test engine to accept methanol fuel.
2. Build an experimental catalytic reactor system for the dissociation of methanol fuel into di-methyl ether (DME), and to feed the DME into the engine intake air.
3. Test the performance of the engine/reactor system.
4. Analyze the test program results and formulate conclusions.

The overall goal of the work was to advance the understanding and development of DME generation as an ignition assistance device to the point where it would be possible to state whether it could be a practical proposition for a working vehicle.

Following a meeting in June 1989, between SMI, ORTECH and Energy, Mines and Resources, the original objectives were modified as follows:

1. No change.
2. Build an experimental metering system to introduce bottled di-methyl ether into the inlet air stream of the engine, in order to simulate the action of a catalytic reactor device.
3. Test the performance of the engine when running with the DME metering system.
4. No change.

C. METHODOLOGY

The conduct of the project was divided between SYPHER:MUELLER International Inc., as project manager, and ORTECH International as subcontractor. SMI was responsible for overall management, investigation of parallel work, liaison with outside parties and assessment of commercial possibilities. ORTECH handled all design and configuration of project equipment, testing of the methanol engine and interpretation of test results.

The test engine was a two cylinder Cummins 4-stroke diesel, derived from the 10 litre "L10" 6-cylinder truck and bus engine. Appendix A gives a description of the engine and the modifications made for operation on methanol. Only one cylinder was operational, the second being retained for balancing. The engine was owned by Cummins Engine Company, which offered its use for the project, and provided technical support and information during the engine conversion and testing program.

The engine was fitted with a glow plug to provide ignition of the methanol fuel, which was injected through the fuel injector as for the normal diesel configuration. The test program included a comparison of engine performance when operating using the glowplug for ignition, and when using DME. The glowplug case was regarded as a baseline, since glowplugs are one of the most common ignition assistance devices in use. Emissions tests were carried out according to the U.S. "13-Mode" federal test procedure, which is now obsolete for commercial engine certification, but remains valid for direct comparison work. DME ignition testing included measurement of the amount of DME required to produce reliable combustion. This amount was expressed as a proportion by mass of the total fuel consumed by the engine, the balance being supplied as liquid methanol through the fuel injector. Generally the objective was to determine the minimum amount of DME required for consistent ignition at various load and speed points.

Part of the project involved investigation of prior work in the field. The most prominent work completed at the time was carried out by the Department of Scientific and Industrial Research of the Government of New Zealand. The Solar Energy Research Institute of Golden, Colorado, had also built and tested a dissociated methanol car for the U.S. Department of Energy. In early 1989, as the project was starting, the New Zealand researchers announced the successful installation of an exhaust heated catalytic DME generator in a pickup truck powered by a small 4-cylinder compression ignition methanol engine. The truck was undergoing road testing and demonstrating good performance. In view of this it was decided that there was nothing new to prove by continuing with design and construction of a reactor device, and that the project funds would be better used in investigation of engine operations, particularly exhaust emissions. The New Zealand project had not investigated this aspect, being more concerned with vehicle serviceability and practicality of the conversion. The U.S. Department of Energy work was not comparable, since it concerned the use of methanol completely dissociated to hydrogen and carbon monoxide in a spark-ignition engine.

The project proposal originally called for an electrically heated DME generating catalytic reactor, in order that output rates could be controlled by varying the electric input current. This was substituted by simple pressurized cylinders of prepared DME, with a precision metering valve and flow measurement system to administer the gas into the inlet air stream of the Cummins engine. Appendix A contains a description of the engine testing schedule.

The original project proposal included provision for some assessment of the practical aspects of installing DME generation apparatus on a working vehicle, and the commercial possibilities for quantity production. These tasks lost importance with the change in project focus. In addition, the project duration overran the planned schedule due to a late start and the subsequent changes in scope, and the time available for commercial assessment work was greatly diminished.

The information derived from the project was not sufficient to form a balanced analysis of the practical and production aspects of DME vehicles and the project was curtailed, allowing for the possibility of more detailed work on these aspects in the future.

II RESULTS

The main body of project results and interpretive comments are contained in Appendix A.

III DISCUSSION OF RESULTS

The testing program demonstrated that DME may be used as an ignition assistance for methanol fuel in a heavy duty engine. The performance capabilities appear to be at least as good as glow plug ignition assistance in terms of power output and engine efficiency. There are apparently potential gains in smoothness of engine operation at low speeds and loads.

Exhaust emissions exhibited a remarkable order of magnitude decrease in total hydrocarbon (THC) output, when tested according to the 13-mode federal test procedure. CO and NO_x both increased by 10% to 20% and CO_2 decreased by about 10%.

The project experimental apparatus offered a number of advantages in comparison to a practical self-contained on-board DME generator. The DME was pure and free from traces of unconverted methanol and water vapour, and it was easy to vary the supply rate independently of engine condition. During the project there was some discussion regarding the possibility of deliberately contaminating the DME in order to investigate the effects on emissions, but this was not put into practice.

The results for engine efficiency must be judged only as a comparison between DME and glow plug ignition. The absolute efficiency is low because the single operating cylinder had to drive the inoperative second cylinder in order to preserve acceptable dynamic balancing of the engine.

The results are primarily concerned with comparing DME ignition to glow plug ignition. This comparison is valid inasmuch as glow plug ignition is the most common method currently used for ignition assistance in methanol heavy-duty engines. There may be particular advantages associated with other ignition methods, e.g. spark plugs, which were beyond the scope of this project to examine.

IV PRACTICAL AND COMMERCIAL CONSIDERATIONS

A. PRACTICAL ENGINE INSTALLATION

Complete self-contained DME generation and ignition systems, such as that constructed in New Zealand, use exhaust heat to operate the catalytic reactor. A complete system consists of the following components:

- Methanol fuel feed pump and control valve;
- Catalytic reactor bed;
- Control valve and feed lines for admitting DME to inlet manifold;
- Water disposal system;
- Control equipment; and
- Auxiliary electric heating element

All of this equipment is additional to the regular fuel injection system, which provides the main charge of liquid methanol fuel. The control system must provide a link between the DME and fuel injection systems, in addition to controlling the DME system itself.

The engine cooling system heat cannot be used since the dissociation process requires much higher temperatures. Generation of di-methyl ether is an intermediate step towards the total dissociation of methanol into hydrogen and carbon monoxide. It produces water as a by-product, and the system must provide for disposal of this water (steam) in a way which will not affect other vehicle components, or the vehicle operator's field of vision.

The auxiliary electric heater is necessary for starting, when no exhaust heat is available. It may also be required to supplement exhaust heat at idle and low-load conditions. The test work demonstrated that DME demand increases as speed and load fall. The major challenge in construction of a working system would be to ensure sufficient reserve generation capacity for the low load/low temperature engine conditions, without producing a reactor of excessive size and wasted capacity for most normal engine operations. Extensive use of supplementary electrical heat would require a significant increase in vehicle alternator and battery capacity. Increased battery capacity would also be required for reliable starts, since the reactor heating demand would occur at the same time as the starter motor operation

The reactor bed must be strongly constructed of corrosion-proof materials, in order to safeguard against methanol fuel leaks directly onto the exhaust manifold. The system requires that methanol is conducted through the hottest part of the engine, and obviously all fuel lines, and gaskets etc. must be designed to minimize the chance of leaks and fire.

B. COMMERCIAL POSSIBILITIES

The principle of using di-methyl ether as an ignition assistance device for methanol engines has two possible commercial applications, which may be summarized as follows:

1. Ignition assistance source for total, or a significant part of the engine operating range, i.e. substitute for glow plugs, spark plugs, additives etc. as used in methanol designs to date.

2. Cold starting aid to supplement glow plugs or other devices at low temperatures.

When this project was proposed, in late 1988, there was a good deal of interest among companies investigating methanol regarding a substitute for current forms of ignition assistance. Generally glow plugs and spark plugs and their associated electrical and electronic systems were lacking in reliability, and fuel additives were excessively expensive.

Since that time Detroit Diesel Corporation has built, tested, and placed into limited production a methanol engine which has a high (23 to 1) compression ratio, and requires glow plugs only for cold starting and warm-up. The combination of the high compression heat and DDC's proven scavenge air control system provides auto-ignition under all normal operating conditions. The same principle of high compression ratio has also been demonstrated on a four-stroke engine by Saab Scania. The Scania engine is fuelled with ethanol and also uses a 1% to 2% dose of "Avocet" ignition enhancer additive. Detroit Diesel has attempted to eliminate glow plugs ever since its first efforts at designing methanol engines, and has now almost succeeded in that objective. Caterpillar Inc., which experienced frequent glow plug failures during the Project "MILE" methanol vehicle testing program, believes that glow plug life could be dramatically improved if plugs were designed and constructed especially for the continuous service situation in a methanol engine. Virtually all designs used to date were designed for engine start pre-heating service only. Cummins Engine Co., maker of the engine used for the project tests, has operated all of its methanol engines on additive enhanced fuel. All three of these companies have methanol heavy-duty engines currently in use in fleet trials. Detroit Diesel Corporation has well over 50 engines in service as part of an extensive development program leading up to commercial production of a methanol engine in 1991. Cummins has engines in trucks and buses, using 5% ICI "Avocet" ignition enhancer. Caterpillar has only one engine in service, a 10 litre 3306 series unit fitted in a truck. It uses modulated power, continuous operation, glow plugs for ignition. Many of these fleet trials are based in California. The State of California has identified methanol as a leading alternative fuel for heavy-duty engines, and is actively encouraging the use of methanol vehicles. Navistar International Corporation and Ford Motor Company are also placing methanol trucks in service in California in the summer of 1990. FEV Limited, a company well known in European alternative fuels research, has developed designs of specialized methanol glow plugs. These have been tested in DDC engines, and in FEV's own methanol engines, with good results. Spark ignition systems, exemplified by MAN engines as used by Seattle Transit, still suffer from short spark plug life. However, MAN is not expanding its methanol engines involvement in North America at present. The North American methanol engine producers fall into

two groups regarding the possibility of commercializing a new form of ignition assistance. Detroit Diesel Corporation alone makes up the first group. DDC has essentially solved the ignition problem, is preparing for quantity production, and has no need of any new system. The second group, consisting of all the other manufacturers, is not engaging in large scale methanol development work or fleet trials. Members of this group have limited budgets available, and prefer to stay with refinements to their existing ignition system designs rather than try completely new avenues.

Every diesel engine manufacturer is fully engaged in preparing designs to meet the 1991 and 1994 EPA exhaust emissions regulations. Uncertainty regarding future emissions and/or alternative fuels mandates has forced manufacturers to split their research work at least three ways in order to cover possible future markets. The primary fuel choices are methanol, natural gas, and diesel. Methanol research is almost totally applicable to ethanol. Most companies have devoted by far the greater proportion of their research and development effort into continued diesel work, which has resulted in the recent wave of "clean diesel" technology. Diesel engines are now expected to meet the 1994 EPA emissions standards. At the same time considerable lobbying by the natural gas industry, coupled with new developments in gaseous fuel injection equipment, has stimulated interest in natural gas engines. The result has been to restrict funds and effort available for methanol.

All of these factors combine against any present interest in the use of DME ignition assistance on the part of engine manufacturers. An on-board DME generating system is at least as complicated as most other forms of ignition assistance, demands complex control strategies, and introduces an element of extra fire risk because of the need to conduct fuel into high temperature areas. The great reduction in total hydrocarbon emissions demonstrated in the project tests is a potential sales point. However it loses much of its impact since manufacturers can meet the future standards using current technologies, and will not introduce new systems to pursue goals which they do not have to reach.

Heavy duty compression-ignition engine development work at the present time is almost all directed towards vehicular applications, because of the pressing need to meet EPA emissions standards. There are many signs, particularly in emissions-conscious areas like California, that public attention is turning also to regulating exhaust emissions from off-road and stationary engine applications. Detroit Diesel Corporation has begun exploring methanol fuel for powering generating sets. It is also testing a methanol version of its high-horsepower 149 series engine, which is widely used in industrial applications for generating sets, pumps etc. DME ignition assistance would be much easier to apply to an engine working at constant speed and relatively constant load, in contrast to the extreme variations of speed and load characteristic of vehicle work. The control system could be much simpler. A vehicle system would have to be compact, extremely robust, and capable of operating under conditions of acceleration, braking, tilting, vibration, and road spray and weather effects. The normal stationary installation is free of all these problems. A practical stationary engine DME generator could be permanently electrically heated, thus simplifying the balance of DME output to engine requirement. Alternatively, an exhaust heated system would be much easier to arrange in terms of optimum size, shape and location, since the engine duty cycle could be predicted with much more accuracy.

Cummins Engine Company indicated that it regarded stationary engine use as a more promising application for DME than vehicle applications. Cummins manufactures a range of engines competitive with the DDC 149 series from 1,000 bhp to 2,500 bhp. Caterpillar Inc. is also very prominent in this field. All three companies also market extensive ranges of smaller industrial engines.

Several organizations in the U.S.A. and Canada have shown interest in the possibilities of converting existing diesel engines to run on methanol. Currently the easiest way to do this is with a fuel ignition enhancer additive, such as ICI "Avocet". For stationary engines it might be possible to derive a range of modular DME generators, either electrically or exhaust heated, which would form a simple "bolt-on" methanol conversion device. The only internal engine modifications required would be larger capacity injectors, possible changes to the fuel supply pump, and appropriate material changes for seals, fuel pipes etc. The converted engine would operate on 100% methanol fuel, avoiding the incremental cost of fuel additive and the complication of arranging for correct additive blending.

There is also promise in the concept of using DME for cold starting assistance only. A cold start package would be different to a full ignition assistance device in a number of ways, including the following:

1. Simpler construction

2. Electrical heating only

3. No complicated dynamic control system

4. No need for fuel in the hot exhaust area.

DME cold starting assistance could be equally valuable for compression ignition and spark ignition engines. Spark ignition methanol engines frequently use an auxiliary gasoline supply for cold starting, and the DME method has the advantage of eliminating the need for a second fuel system.

Glow plugs, spark plugs and pilot diesel injectors cause problems for engine designers in another very important respect apart from their extra cost and complication. It is not an easy matter to provide a location for a glow plug inside a cylinder head. Modern diesel engines frequently use four valves, and there is little room left for any other components beside the fuel injector. Heads are designed with great care to eliminate weak areas and sections which can lead to cracking and consequent major engine damage. The necessary water passages for cooling complicate matters even more. In addition, it is not always desirable to simply place the glow or spark plug wherever it will fit, because its position can have an effect on combustion propagation, and hence emissions characteristics. Even if glow plugs are only used for cold starting their simple physical presence can be a potential source of serious engine weakness.

For this reason, the idea of totally eliminating glow plugs and achieving cold start by means of a reasonably cheap and simple external DME generator could be attractive to engine designers. The project in its revised form did not examine the question of the electrical power required for DME production. A glow plug typically draws 10 to 12 amperes current from a 12V system, representing around 1 KW power for a 6 cylinder engine. This may be regarded as the amount of power available for DME generation which would cause no extra cost or complication to the vehicle electrical system in comparison to glow plugs.

V CONCLUSIONS

- Di-methyl ether (DME) may be used as an ignition assistance device to allow compression-ignition engines to operate on methanol fuel.
- An engine may be started at moderate temperatures, and run through its entire rated load and speed range using DME assistance only to promote ignition.
- The proportion of DME required for proper engine operation, expressed as a fraction of the total mass flow of fuel consumed, diminishes with increasing engine speed and load.
- DME may be produced from methanol by an exhaust heated catalytic reactor device so that a vehicle fitted with an on-board reactor need only carry methanol fuel.
- DME assisted combustion, when compared to glow plug assistance, shows a drastic reduction in total hydrocarbon output (THC) in tests according to the 13-mode U.S. federal test procedure, a slight reduction of CO_2 output, and slight increases in CO and NO_x emissions.
- The essentially uncontrolled ignition of the DME, ahead of the main charge of methanol, did not produce any unacceptable in-cylinder pressures or pressure rise rates.
- Engine idling and low speed, low load operation, using DME was smoother and less liable to misfiring than glow plug operation.
- Engine fuel efficiency was almost the same for DME and glow plug operation.
- Recent advances in methanol engine ignition methods have much reduced the need for glow plugs. This has probably eliminated any opportunity for commercialization of DME as a primary ignition assistance source for vehicles. Opportunities may remain for use on stationary applications with constant speeds and loads, e.g. generators.
- The use of on-board DME generation as a cold starting aid for methanol engines offers several advantages and may be commercially applicable to compression ignition and spark-ignition engines.

VI RECOMMENDATIONS

1. Test DME ignition assistance performance against other methanol ignition methods, e.g. spark plugs, fuel additives, to confirm whether THC emissions reduction is consistent.

2. Design and construct a catalytic reactor for installation on a production constant load and speed engine such as a generator set, and test power output, efficiency and emissions performance.

3. Investigate design of a simple electrically heated catalytic reactor for use as a cold start device, including power required per unit DME output, and practical aspects such as methanol feed, water disposal and DME metering to engine.

Appendix A

DME Project: Final Report
ORTECH International, May, 1990

APPENDIX A

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SUMMARY

Methanol is one of the leading alternatives to diesel fuel and gasoline. In diesel applications, methanol's low cetane number has necessitated the use of glow plugs, spark plugs or expensive additives for ignition assistance.

This report covers the use of Dimethyl Ether (DME) as an ignition improver for neat methanol in a compression ignition engine. Gaseous DME was admitted to the intake air stream of a four-stroke test engine operating directly on injected methanol. The amount of DME required to achieve stable operation over the load/speed range of the engine without the use of a glow plug was determined. DME's effect on ignition delay and rate of pressure rise is discussed. Exhaust emissions were measured and compared with operation on methanol with glow plug assisted ignition. Hydrocarbon emissions were reduced by a factor of 10 at light loads. Aldehyde emissions were also reduced.

I INTRODUCTION

Methanol is one of the leading alternatives to diesel and gasoline. In diesel applications, methanol's low cetane number has necessitated the use of glow plugs, spark plugs or expensive additives for ignition assistance. The primary method of assisting the compression ignition of methanol, chemical additives aside, is to raise the temperature of the environment into which the neat methanol is injected. Possible techniques for creating this thermally activated environment are: intake air heating, glow plugs, high compression ratios or the retention (or recirculation) of burnt exhaust gases [1]. Each of these techniques has drawbacks which limit its application. Intake air heating has high power demands. Lack of durability with glow plugs continues to be a problem. High compression ratios put considerable stress on existing hardware. The difficulty of attaining and controlling exhaust gas retention or recirculation in a four-stroke engine make its use unsuitable for many engines.

The technique used in this program was to introduce a small amount of DME into the intake air. The DME/Air mixture begins a slow combustion early in the compression stroke. This combustion heats the remaining air in the charge and creates an ideal environment for igniting the subsequently injected methanol. This method was investigated in the early 1980's by Brook, Rallis, Land and Cipolat [2]. The results were very positive regarding the ability to operate an engine over the full load and speed spectrum, but no emission study was done at that time.

The major advantage of this type of ignition enhancement system is that the DME can be produced by the dehydration of methanol via a catalytic reaction. The reaction is exothermic over the temperature range 570 - 620K[3], but requires some heat to initiate the reaction and vaporize the methanol. This heat could be supplied from the exhaust gases of the engine. Before designing such a catalyst, two questions must be answered. One, the rate at which the catalyst must produce DME and two, whether the emissions resulting from the addition of the DME would render this technique undesirable.

The objective of the present project is to find the ratio of DME to methanol which will allow the operation of a heavy-duty diesel engine throughout its speed/load range, without other forms of ignition assistance. Also, to study the impact of this method on exhaust emission compared to methanol operation assisted by a glow plug.

II EXPERIMENTAL SET UP

2.1 Engine and Equipment

A single cylinder Cummins L10 diesel engine was used for the test. The engine consists of the rear two cylinders of the typical 6-cylinder L10 where one cylinder is used for dynamic balance only. The balance piston has had a large opening cut through it to reduce compression work and the valve gear has been disconnected. The auxiliary systems required to operate the single cylinder L10 engine include: external oil pump, external coolant pump and heat exchanger, and an external fuel cooler. The engine had the following specifications:

Bore:	125 mm
Stroke:	136 mm
Displacement:	1.669 litres
Compression Ratio:	18:1
Crank Length C-C:	218 mm

A high lift cam (F-1419), along with a methanol injector, was used to supply the extra volume of methanol required. The injector, (9-10-250), had a 9 hole spray pattern at a 10 degree inclination from the piston radius. A stock quiescent "Mexican Hat" piston was used throughout the program. The injector and cam combination were set to a static timing of 0.130 in., yielding beginning of injection timing from 8° ATDC at idle to 12° BTDC at full load, and an end of injection which remains almost constant at 28° ATDC. This timing was kept constant throughout all the testing. A strain gauge was applied to the injector-plunger/rocker-arm connecting link to dynamically monitor injection timing. The cylinder pressure was monitored with an AVL pressure transducer threaded into the side of the head and connected to the combustion chamber by a small passage. The signals from the pressure transducer, the injector link, and a crank angle encoder, were fed to a Norland high speed digital storage scope for recording and later analysis. Turbocharging was simulated by a blower used to compress the intake air and an exhaust manifold throttle to simulate turbo backpressure. As shown in Figure 1, a glow plug (NGK Y119) was located between the intake and exhaust valves. The glow plug had a resistance of 0.5 ohms and was powered by an external power supply.

Bottled DME was used for testing. Appendix A contains the specifications of the DME. The bottle was placed in a constant temperature bath to stabilize the vapour pressure, by supplying the required heat of vapourization when the gas phase was to be drawn off. The DME flow, controlled by a precision needle valve, was measured with a mass flowmeter (Hastings STH), and then fumigated into the intake manifold approximately 10 in. before the head.

2.2 Test Procedure

The testing procedure followed was "Diesel Engine Emission Measurement Procedure, SAE J1003, Feb. 1984", more commonly known as the "13-mode test". Table 1 outlines the 13-modes used for the L10 single cylinder engine.

Table 1. 13-Mode Points

Mode #	Speed RPM	Load %	Load ft.lbf
1	800	0	0
2	1300	2	2
3	1300	25	26
4	1300	50	53
5	1300	75	78
6	1300	100	105
7	800	0	0
8	1900	100	72
9	1900	75	54
10	1900	50	36
11	1900	25	18
12	1900	2	1
13	800	0	0

The initial tests, numbers 3 and 4, were done as a baseline for methanol/glow plug performance. The glow plug current was maintained at 12 amps for all glow plug tests. At each mode, performance data were recorded, 32 consecutive cylinder pressure and injector link traces were recorded, one average trace made up of 40 consecutive traces was recorded, and emissions measurements of CO, CO_2, NO_x and THC's were taken.

The next test, number 5, was to map the performance of the engine with various DME/methanol fuel ratios. At each operating point, the amount of DME would be varied in steps. At each step, once the DME flow was set, the methanol flow would be adjusted to yield the set point required torque. The lower substitution level of DME was determined by the onset of misfire or unstable operation. The upper level was determined when there was no further improvement of ignition delay, or when efficiency began to drop and there was stable operation. It is interesting to note that knock was not a significant factor in these tests. This may have been due to the steady-state nature of the testing, or that the levels of DME were not great enough to produce knock when the upper level criterion had been met.

Having determined the operating envelope in test number 5, test number 6 was to determine the emissions trends with varying amounts of DME within that envelope. From the results of this test, the optimum operating points were determined and collated to produce test number 7 results. The selection criteria for test number 7 results were a combination of low NO_x and THC levels. These criteria did not always select for maximum efficiency, but the variation was slight, usually less than 2%.

Test numbers 8 and 9 measured aldehyde levels on glow plug and DME operation respectively. Test number 9 was also used to determine the fractional speciation of the exhaust hydrocarbons using a gas chromatograph. The gas chromatograph was calibrated for methanol, methane and DME. Cylinder pressure traces, 32 consecutive and 40 trace averages of each mode, were recorded on the digital scope.

2.3 Emissions Measurements

Exhaust emissions were sampled through a Teflon heated sample line at 180 C. From this raw sample stream, a portion was drawn into a Beckman 402 hydrocarbon analyzer. The analyzer uses a "flame ionization detector" to determine the total hydrocarbon content of the gas on a methane equivalent volume basis. The literature on the Beckman analyzer claims a response factor of 0.86 for methanol and 1.0 for DME, relative to the methane standard.

A second portion from the raw gas stream was sent to a Beckman 995 chemiluminescent NO/NO_x analyzer. The remaining sample was chilled and dried and then fed to the CO and CO_2 analyzers. The CO levels were detected by a Beckman 867 non-dispersive infrared analyzer, while the CO_2 levels were measured by a Beckman 864 NDIR.

The SAE J1002 emissions procedure was used as a guideline for the above measurements. This procedure dictated that the emissions be allowed to stabilize for 2 to 4 minutes and then data be taken for the next 2 to 4 minutes, and finally, that the average of the final minute of data be recorded. This procedure yields a smoothed average of the emissions.

To determine the relative makeup of the hydrocarbon emissions, a Varian 1200 gas chromatograph, fitted with an FID detector, was used. The gas chromatograph was injected with a sample of the exhaust stream that had been drawn from the exhaust manifold. The stream entered a Chromosorb 101 packed column, where the stationary material (packing) in the column separated the components by means of the differing affinity of the packings for the component gases. The component gases exited the column sequentially, where they were quantified by the FID and integrated by a Hewlett Packard 3390 integrator. This method yields the analysis of a "batch" of exhaust gas, and is therefore vulnerable to transient concentrations in the exhaust stream.

Aldehyde samples were obtained by drawing a portion of the exhaust gas through a Teflon heated sample line (120 C), into a single midget impinger containing 50 ml of 2,4-dinitrophenyl-hydrazine in acetonitrile. Ten minute samples were taken at each operating mode, at a sample flowrate of 1.5 l/min. After collection, the samples were analyzed using a high performance liquid chromatograph, with a C18 reverse phase column.

III RESULTS

3.1 Ignition Delay, Dp/Dt and Misfires

The engine operating on glow plug assist did run at all the required speeds and loads, however, the operation at light loads was uneven. Operation at 800 RPM idle, 1300 RPM 2% load, and 1900 RPM 2% load, was characterized by numerous misfires followed by a strong firing with a high rate of pressure rise (except at idle where the firing was less explosive due to the late ignition). Figure 2 shows a series of 11 consecutive cylinder pressure traces at idle with glow plug assist. Note the late ignition, numerous misfires and the peak pressure. Ignition delay for light loads at 800, 1300 and 1900 RPM on glow plug operation was approximately 20° crank angle. The operation of the Cummins PT (pressure/time) fueling and injection system make it difficult to precisely locate beginning of injection. This puts ignition delay values in doubt by approximately plus or minus 1.5 crank angle degrees.

Figure 3 shows consecutive traces for DME assisted operation at idle. The ragged shape of the traces was thought to be caused by the resonating of pressure waves in the passage connecting the cylinder and the pressure transducer. The consistency of firing was markedly improved. The ignition delay, not observable on these traces, has been reduced to approximately 10°. Figure 4 shows an average trace at idle conditions (average of 40 pressure traces), for both glow plug and DME operation. Notice the difference in the peak pressure. When this data was first analyzed it was thought that instrument error had created the large pressure change. When all the instruments had been recalibrated the same results were found. Upon analysis, these two traces yielded the same gross indicated power, 3.1 hp for DME and 3.0 hp for glow plug. The average trace for the DME indicates a deviation from motoring pressures on the compression stroke at 25° to 30° BTDC. At idle, with DME assist, the fuel was 60% to 70% DME by mass.

Figure 5 shows average traces for 1300 RPM at 25% of full load. Here again indications of combustion appear on the DME trace at 30° BTDC. Ignition delay has been reduced from 17° to 6° and the firing consistency has greatly improved. Figure 6 shows ignition delay versus load for both DME and glow plug operation.

The introduction of DME to the intake air appeared to have little effect on the maximum rate of pressure rise, as shown in Table 2. Although it does not show up in the data, the engine operation became smoother at light loads on DME. A problem with recording a maximum rate of pressure rise is the lack of a quantitative definition of the parameter. Specifically, over how many degrees of crank angle should one determine the rate of pressure rise.

Table 2. Operating Parameter Comparisons

ENGINE SPEED/LOA rpm / %	GLOWPLUG EFFIC. %	DME EFFIC. %	GLOWPLUG IGN. DEL deg	DME IGN. DEL deg	GLOWPLUG PEAK PRE psi	DME PEAK PRE psi	GLOWPLUG dP/dt psi/deg	DME dP/dt psi/deg
850/IDLE	NA	NA	21	10				
1300/2%	6	3	21	13	683	877	22	43
1300/25%	20	22	17	6	661	903	24	32
1300/50%	27	26	11	8	1185	1190	87	68
1300/75%	31	32	9	8	1620	1666	102	106
1300/100%	31	31	8	7	2098	2067	190	184
1900/2%	4	2	22	12	654	776	22	39
1900/25%	11	14	21	4	650	946	26	56
1900/50%	20	21	15	12	868	1052	30	49
1900/75%	24	24	9	10	1403	1392	103	102
1900/100%	27	26	5	8	1731	1718	106	119

3.2 Performance

The engine performed well on DME. It could be started cold (room temperature of 17 C), and would idle smoothly from the beginning. It could run throughout the required speed and load spectrum. At the higher loads the advantage of adding the DME was minimal. The efficiency of the engine remained relatively unchanged by the addition of DME to the charge air, as shown in Figure 7 and Table 2. This was surprising in light of the reduced misfire. However, as mentioned above, the indicated horsepower was unchanged by the DME and no efficiency gain should be expected. The efficiencies were calculated based on total fuel energy input. That is, the sum of the lower heating values of each fuel, times their respective mass flowrates.

It should be noted that the efficiency levels shown were from a high friction test engine and are really only useful for comparative purposes.

During testing on DME, it was noted that the engine at the 2% load points would sometimes (twice in nine tests), be unable to hold the mode point. The load would fall off and then the RPM would drop. It appeared there was a critical thermal plateau which was unstable at these times. Falling temperature reduced the reaction rate of the DME, which in turn, would further slow the reaction. Unfortunately, there was not sufficient time to explore this phenomenon.

3.3 Emissions

Emissions results were recorded using the procedure described in paragraphs 2.2 and 2.3. The subsequent reduction of those values into useful units of measurement was done using the calculations detailed in the "SAE Handbook Procedure, SAE J1003, Feb. 1984, Page 25.27, Section 5, Alternate Calculations". (Appendix 2). Care was taken to use the appropriate hydrogen to carbon ratio and molecular weight for both methanol and DME. Specifications for methanol and DME can be found in Appendix 1.

Table 3. Emissions Results Comparisons

GLOWPLUG THC g/Kg	DME THC g/Kg	GLOWPLUG CO g/Kg	DME CO g/Kg	GLOWPLUG CO2 g/Kg	DME CO2 g/Kg	GLOWPLUG NOx g/Kg	DME NOx g/Kg	GLOWPLUG ALDEHYDES g/Kg	DME ALDEHYDES g/Kg
225	15	41.62	81	1075	930	3.5	4.7	3.56	1.79
175.38	14.57	41.78	110.99	1067	1050	3.38	4.76	3.43	1.46
21.98	6.01	19.97	22.83	1312	1274	5.44	7.48	1.09	0.63
2.85	1.87	1.26	3.78	1367	1351	8.24	11.51	0.24	0.25
2.33	1.58	1.14	2.29	1368	1356	11.72	14.71		
1.72	1.44	2.19	2.19	1367	1360	13.85	14.49	0.25	0.31
99.87	10.43	31.37	71.36	1188	1144	2.73	2.58	4.82	0.85
55.83	6.88	30.72	38.58	1250	1213	3.36	4.04	1.41	0.70
5.74	3.44	7.36	6.78	1356	1348	6.98	6.71	0.26	0.53
2.39	1.61	1.67	2.39	1369	1360	7.65	8.77		
2.38	1.54	1.54	1.99	1369	1362	9.62	11.28	0.23	0.23

Figures 8 to 12 and Table 3 show the emissions results on a gm/kg fuel basis. That is the number of grams of the indicated species emitted from the exhaust pipe per kilogram of fuel into the engine. The 13-Mode totals for glow plug and DME assist are shown in Table 4.

Table 4. 13-Mode Totals for Glow Plug and DME Assist

Emissions gm/BHP.Hr	Glow Plug	DME
CO	7.8	9.9
CO_2	845	767
NO_x	5.1	5.6
THC	21.7	2.2

Figure 13 and Table 5 show the breakdown of the total hydrocarbon emissions into methane, methanol, DME and aldehydes. On glow plug operation, over 95% of the hydrocarbon emissions were in the form of unburned methanol. The remainder were aldehydes, the majority of which was formaldehyde. The hydrocarbon emissions on DME operation were still largely methanol. However, at low loads, a significant fraction were DME, methane and formaldehyde.

The use of DME as an ignition improver caused a moderate increase in CO and NO_x levels, and a drastic decrease in THC's. The aldehyde emissions were also positively affected.

Table 5. G.C. Analysis of Emissions

		Results From Gas Chromatagraph						
SPEED	LOAD	METHANE	DME	METHANOL	HCHO	CH3CHO	TOTAL HC	TOTAL HC
rpm	%	ppmv	ppmv	ppmv	ppmv	ppmv	ppmv	ppmv
DME							GC	BECKMAN
900	0	14	284	106	38	1	443	472
1300	2	41	123	220	41	1	426	433
1300	25	12	62	229	28	1	332	283
1300	50	1	8	161	13	2	185	167
1300	100	0.6	2	58	19	2	82	71
1900	2	33	80	207	41	1	362	354
1900	25	13	49	142	35	1	240	221
1900	50	4	19	113	28	1	165	149
1900	100	0.6	1	74	12	2	90	101
NO DME								
1900	2	2	0	6465	264	4	6735	6066
1900	25	2	0	2426	97	2	2527	3406
1900	50	1	0	663	13	2	679	568

3.4 Discussion

The use of DME as a means to improve the compression ignition of neat methanol in a heavy-duty engine appears to be a viable option. The mechanism by which the DME aids the ignition of the injected methanol is believed to be an increase in charge temperature, due to the precombustion of the DME. This early combustion exhibited some particular characteristics. The onset of combustion was very gentle with the initial pressure rise being just noticeable. The combustion began quite regularly at approximately 25° to 30° before TDC. This type of gradual combustion had been noted by researchers Shigeru Onishi, Souk Hong Jo, Katsuji Shoda, Pan Do Jo and Satoshi Kato in the late 1970's in two-stroke gasoline engines, and given the name "ATAC" for Active Thermo-Atmosphere Combustion [4]. The result of this gradual reaction is to create, without knock, an environment in which the temperature has been elevated, and thereby enhance the ignition and achieve more complete combustion of the injected methanol. Brook, et al [2] believed the DME partially decomposed to create a "soup of free radicals" which acted as a chemical spark plug for the methanol. A mass fraction burned calculation would indicate if the primary mechanism of ignition enhancement was chemical or thermal, by determining how much combustible DME remained at the point of methanol injection.

IV CONCLUSIONS

It can be concluded from this study that the use of Dimethyl Ether, (DME), as an ignition improver for compression ignition of directly injected neat methanol, is a viable method with very positive effects on engine performance and emissions over the speed and load range of a heavy-duty diesel.

The required amount of DME to produce stable operation of the engine in this study is shown in Table 6.

Table 6. Percentage Fuel Breakdown

Speed/Load RPM %	% Methanol (Mass)	% DME (Mass)
800/0	41	59
1300/2	76	24
1300/25	90	10
1300/50	98	2
1300/75	98	2
1300/100	99	1
1900/2	81	19
1900/25	84	16
1900/50	98	2
1900/75	99	1
1900/100	99	1

The CO and NO_x emissions were moderately increased, while the total hydrocarbon (THC) emissions were drastically reduced, when compared to operation using a glow plug for ignition. The major emission reductions were at light loads. Complete listings of the results are included in Appendix 3.

V RECOMMENDATIONS

These results validate the use of DME as a method for operating a heavy duty methanol diesel. The next logical step is to use this data to design a catalytic reactor capable of producing the required amount of DME directly from the methanol fuel, and testing the system on a multicylinder production engine. A large portion of the catalyst background work in this area has been done by Michael Karpuk and Scott Cowley [5]. A control system to regulate the production and admission of the DME into the engine would also have to be designed and built.

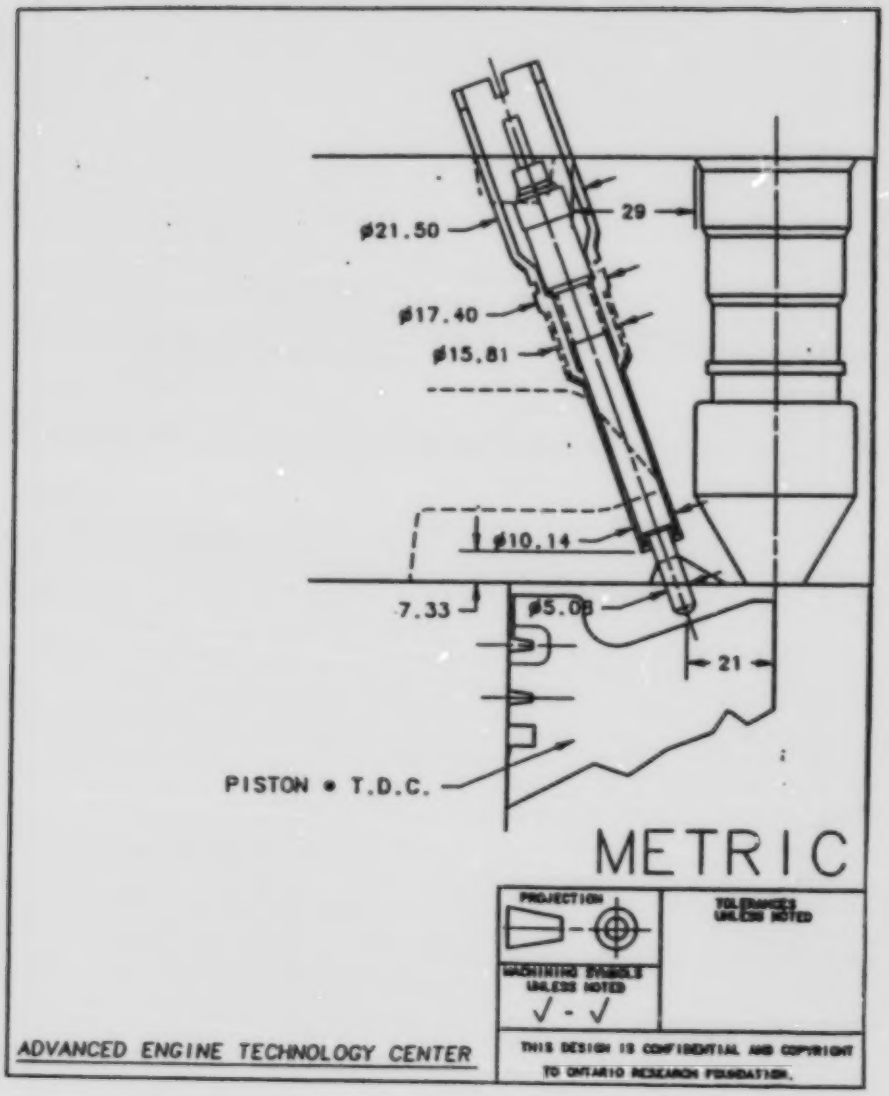

Figure 1. Glowplug Placement in the Cylinder Head

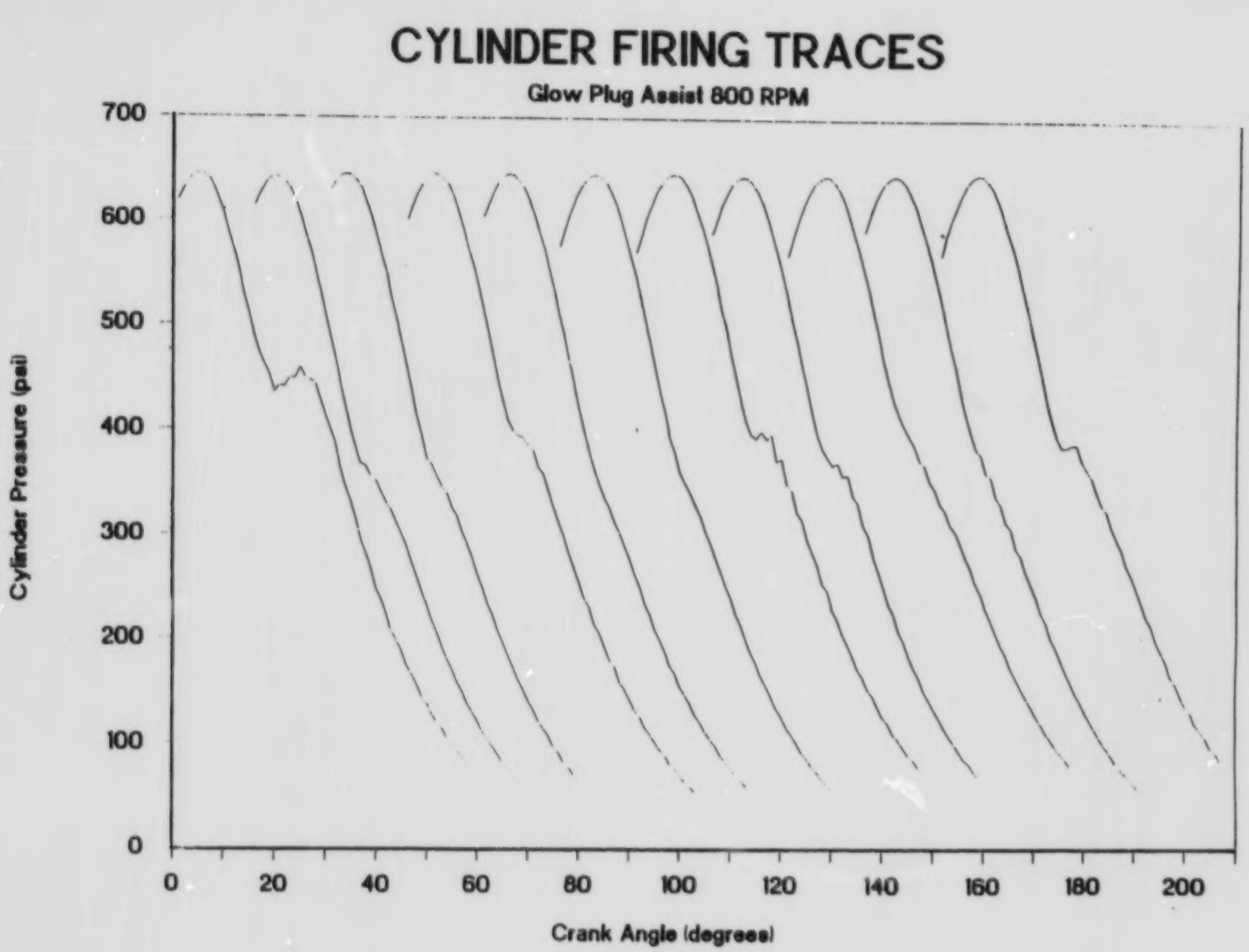

Figure 2. Consecutive Idle Pressure Traces with Glowplug

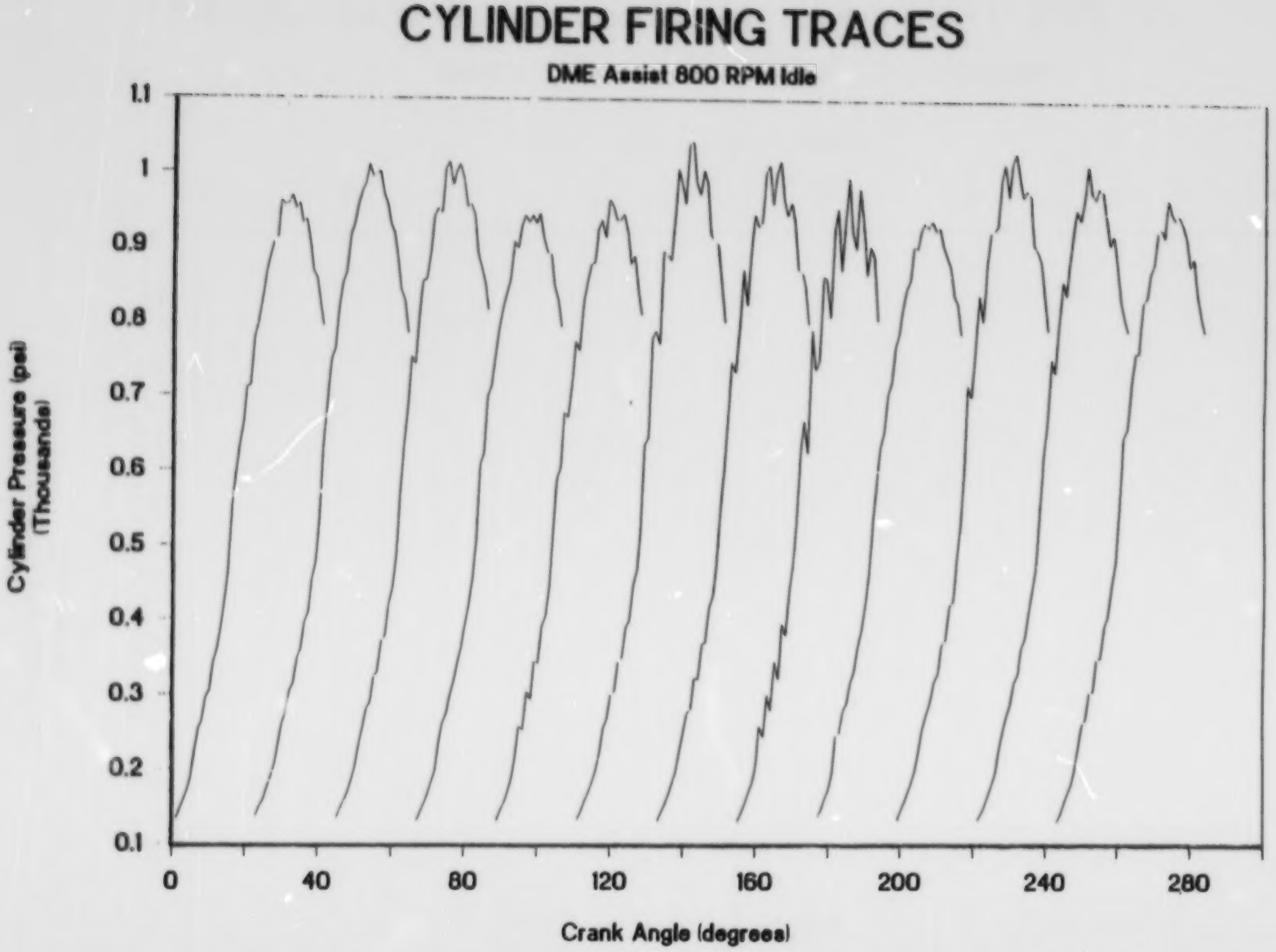

Figure 3. Consecutive Idle Pressure Traces with DME

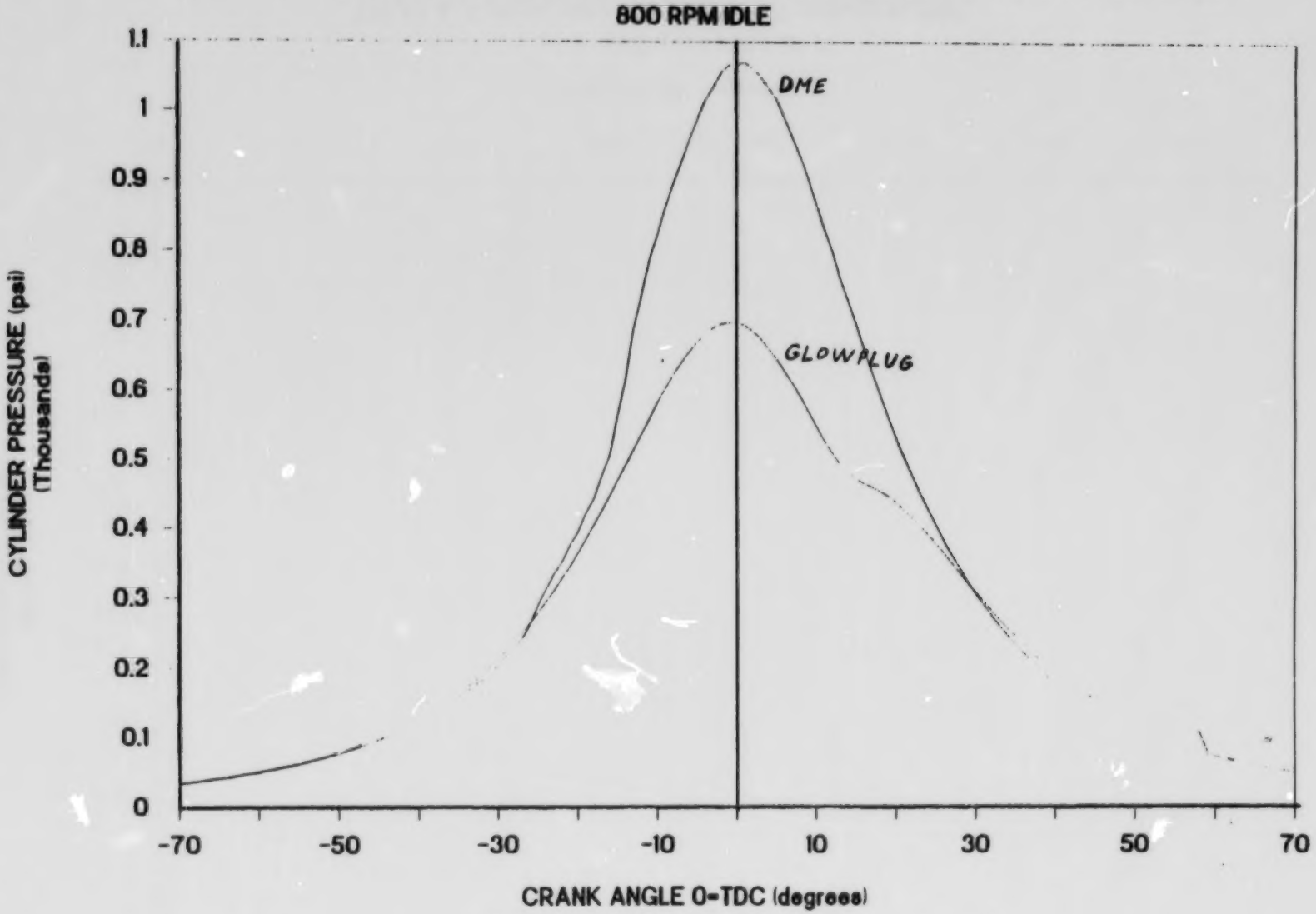

Figure 4. Idle Average Pressure Trace Glowplug & DME

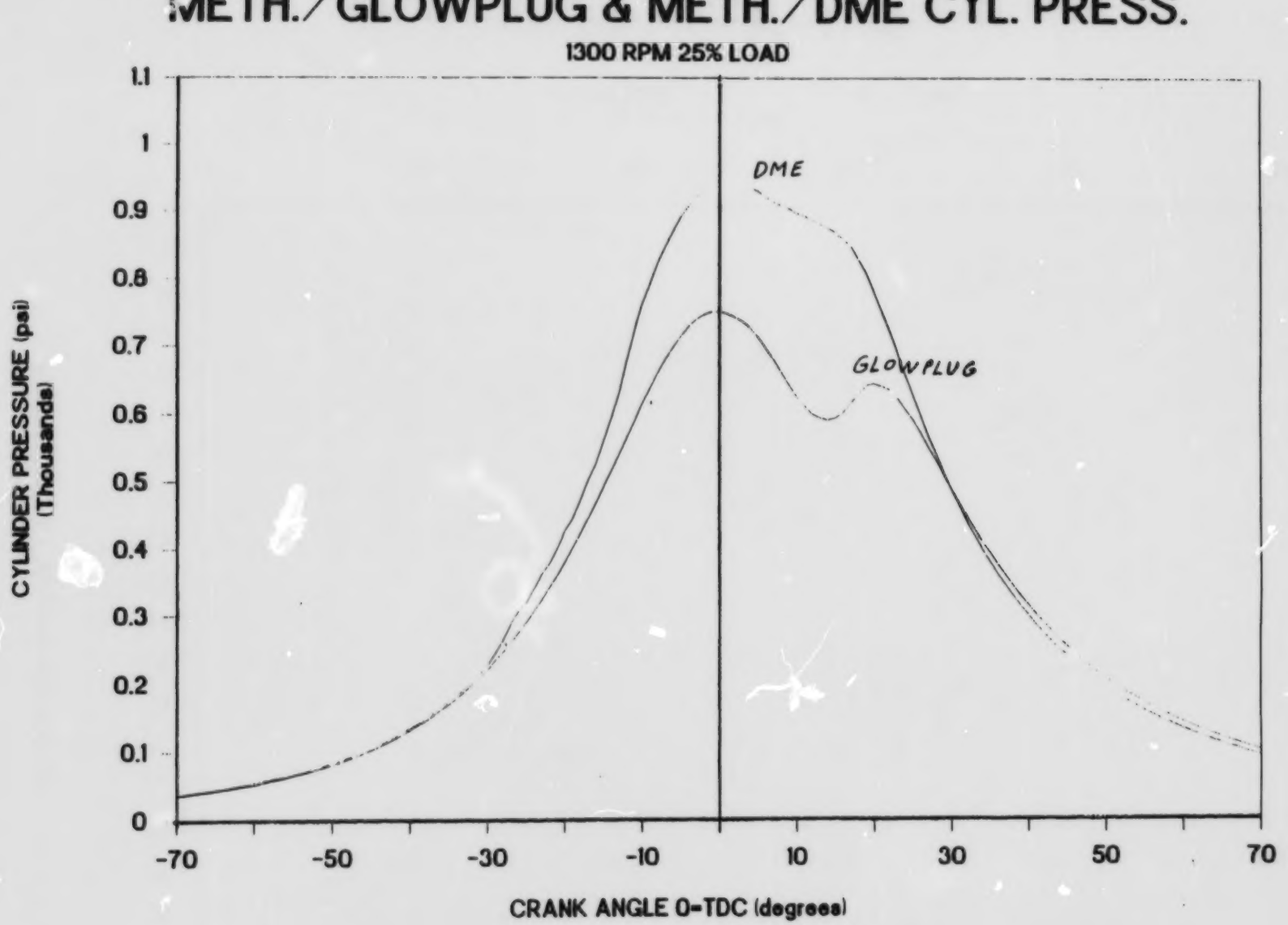

Figure 5. 1300 RPM 25% Load Average Trace Glowplug % DME

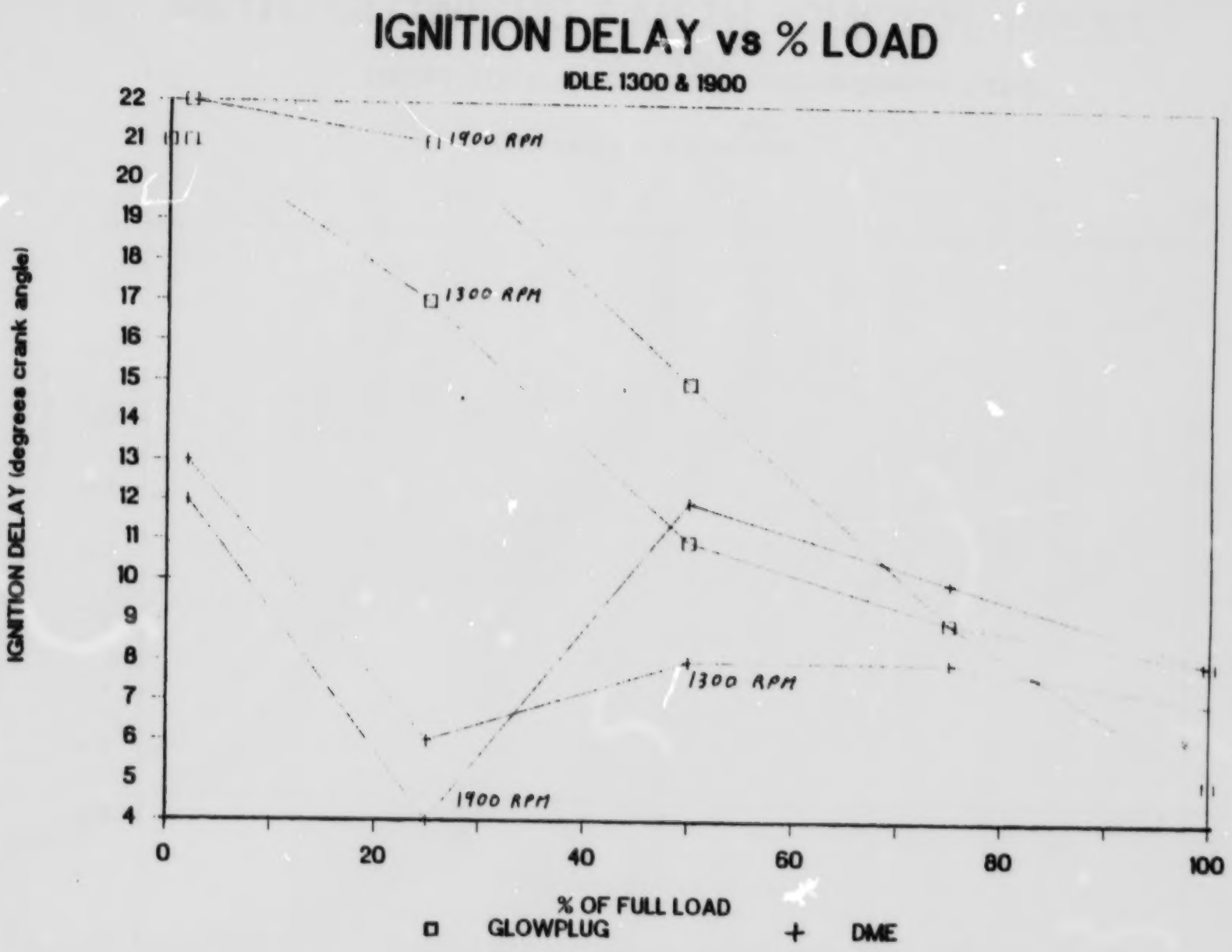

Figure 6. Ignition Delay versus % Load

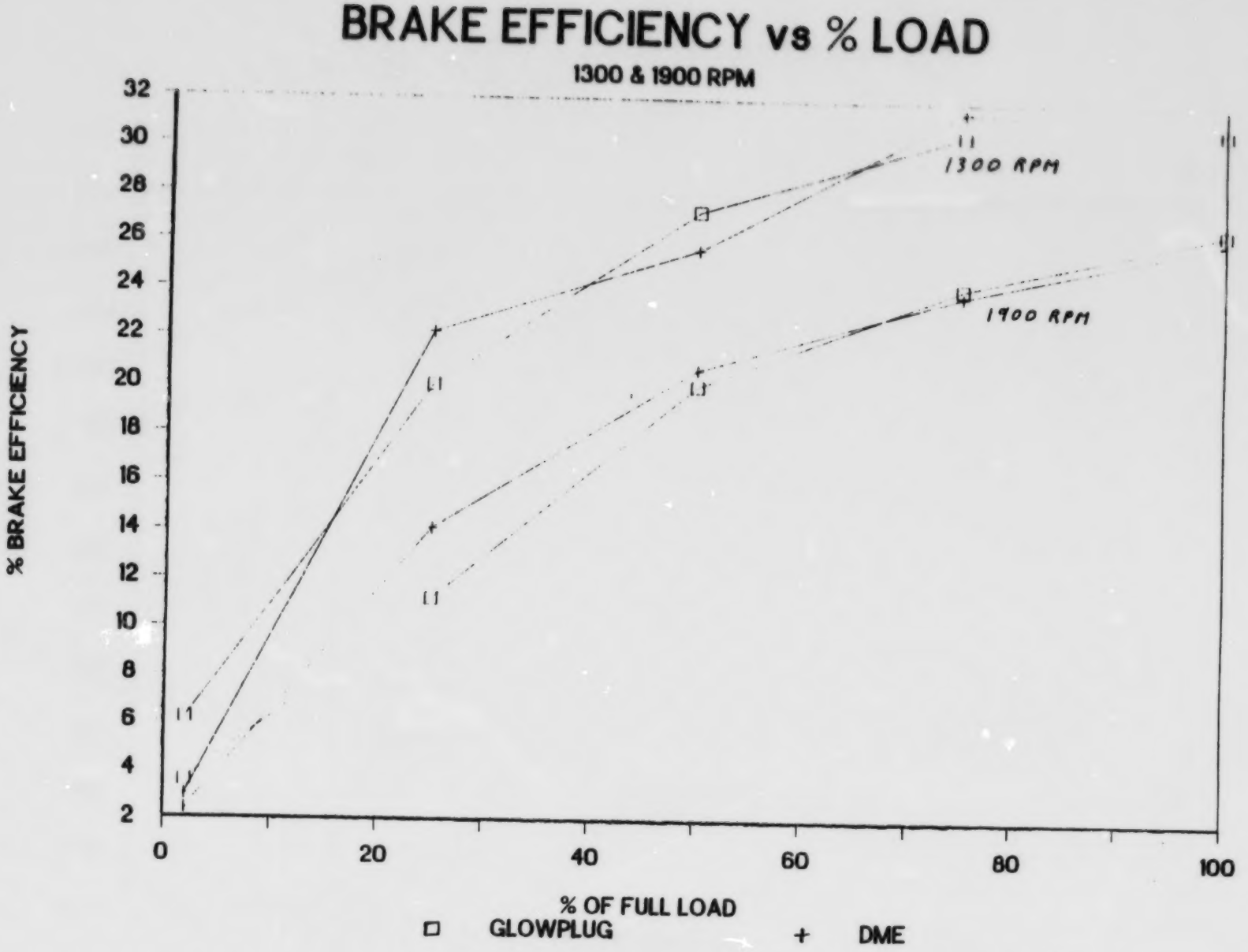

Figure 7. Brake Efficiency

TOTAL HYDROCARBON EMISSIONS vs % LOAD

IDLE. 1300 & 1900 RPM

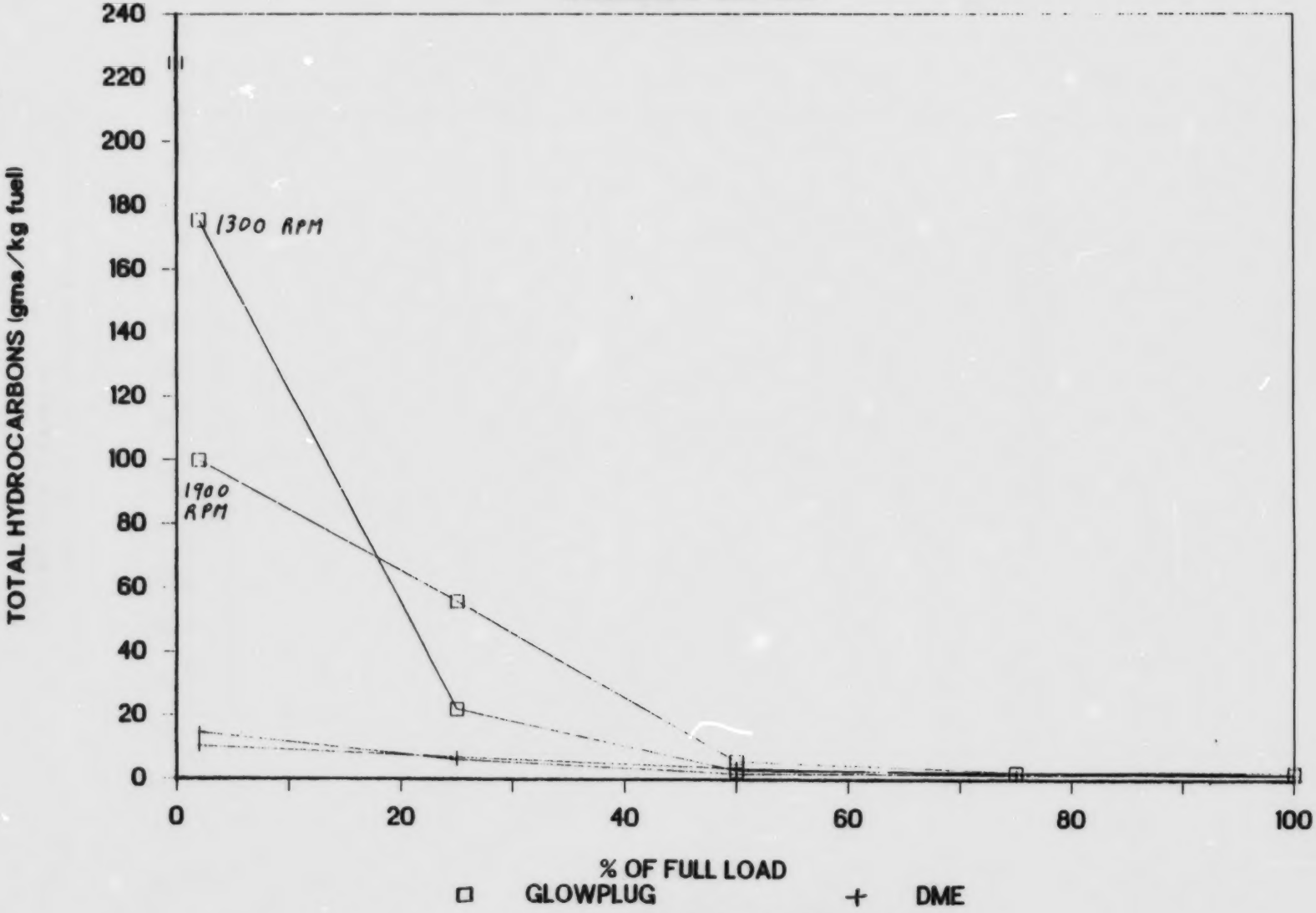

Figure 8. Total Hydrocarbon Emissions

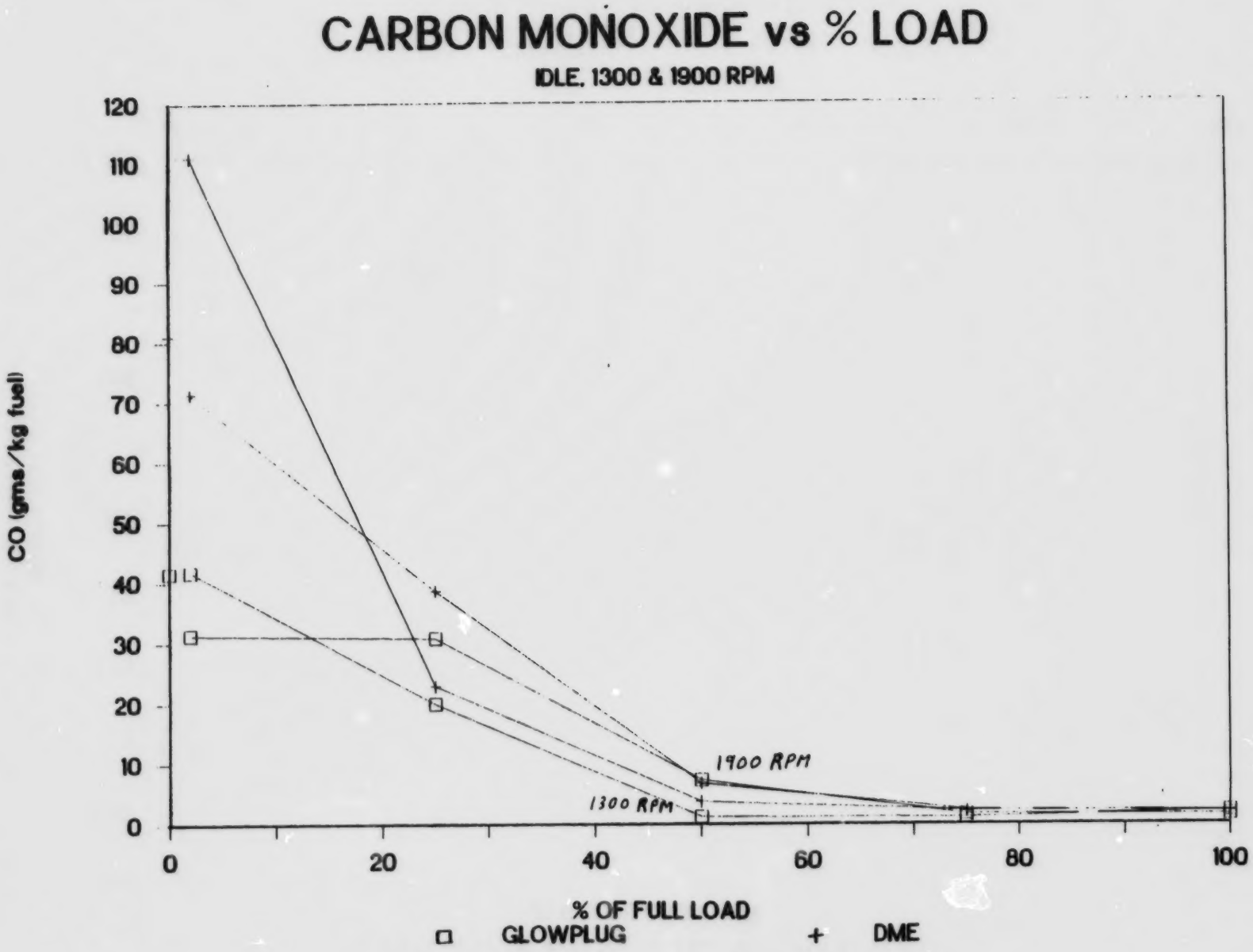

Figure 9. Carbon Monoxide Emissions

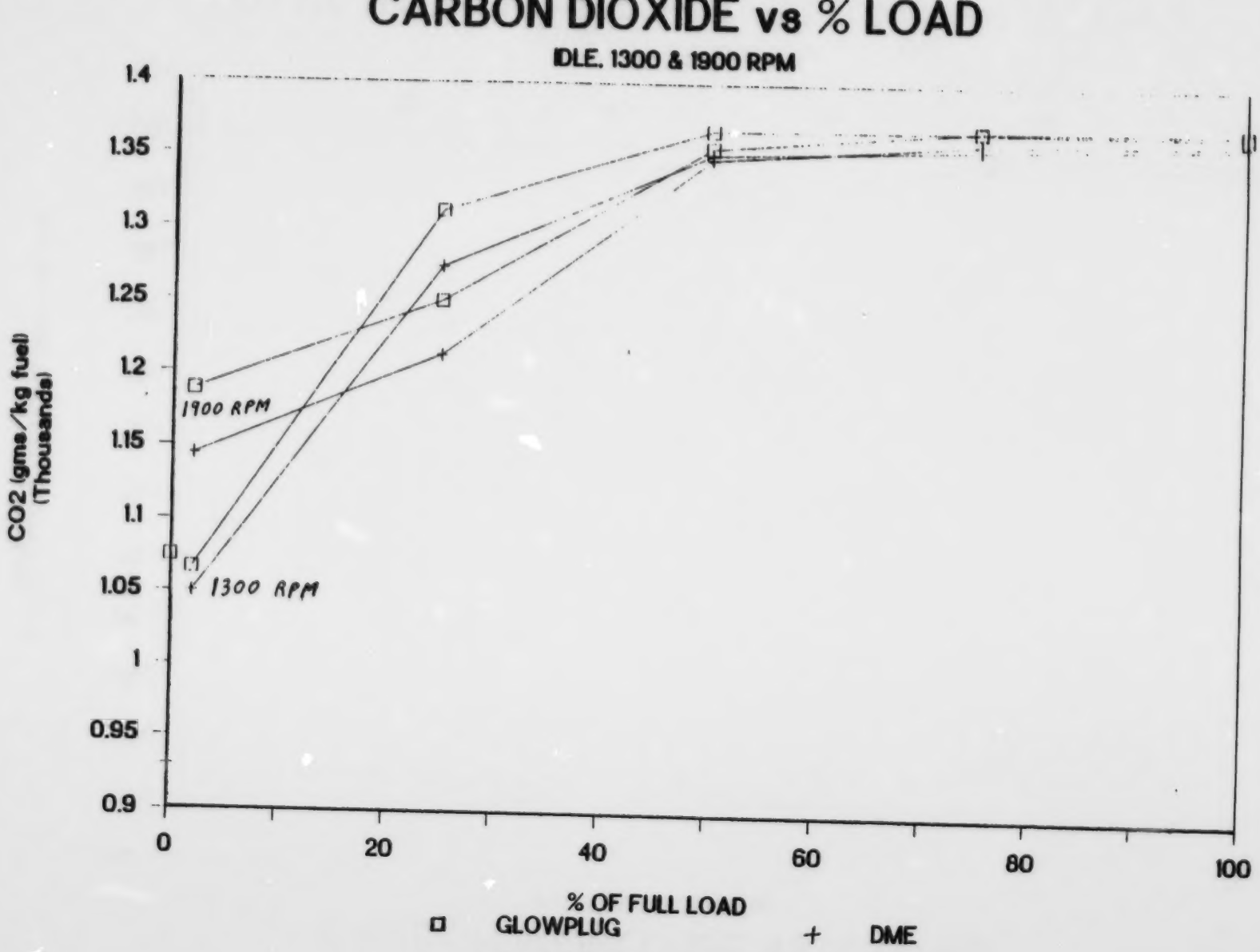

Figure 10. Carbon Dioxide Emissions

OXIDES OF NITROGEN vs % LOAD

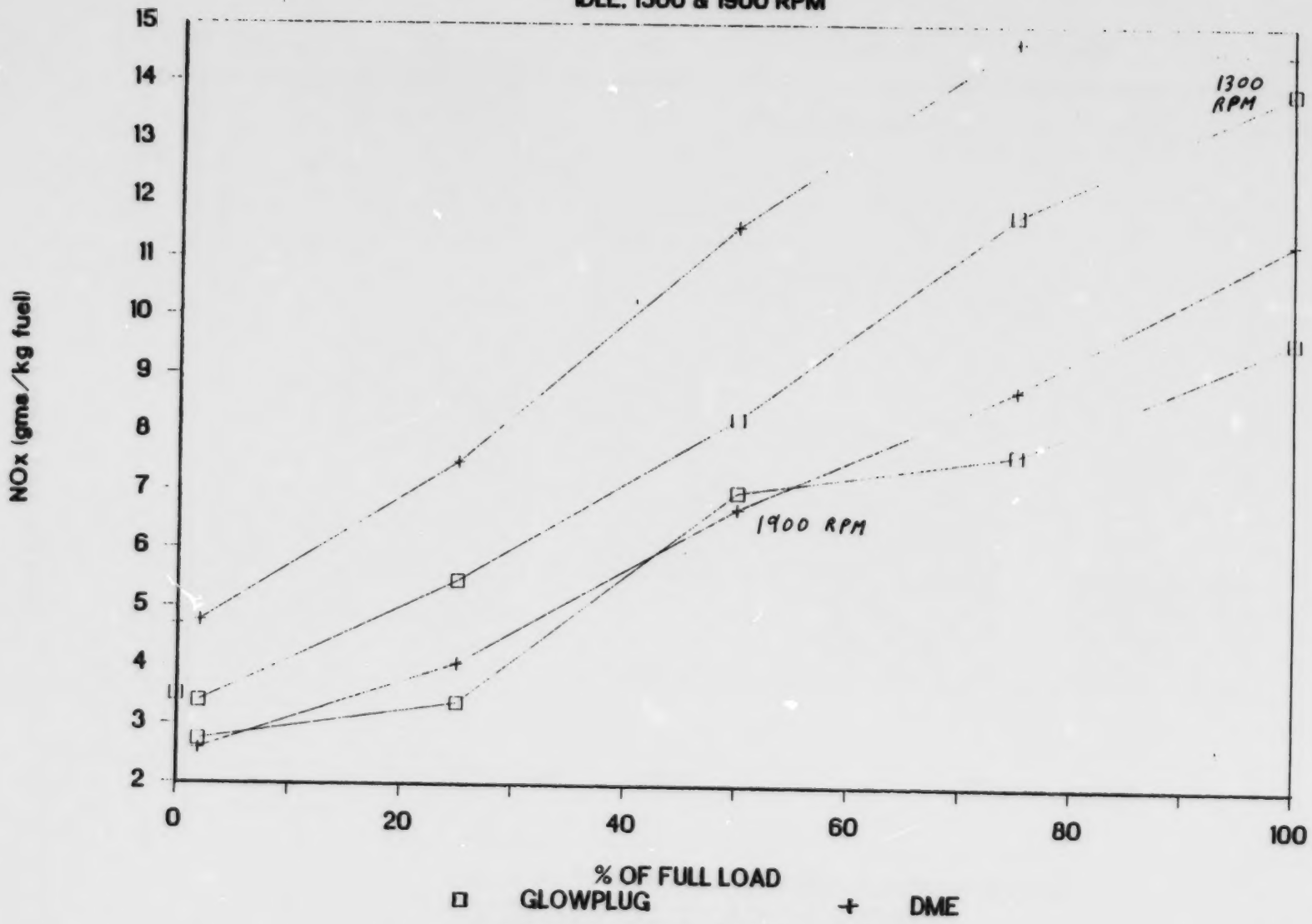

Figure 11. Oxides of Nitrogen Emissions

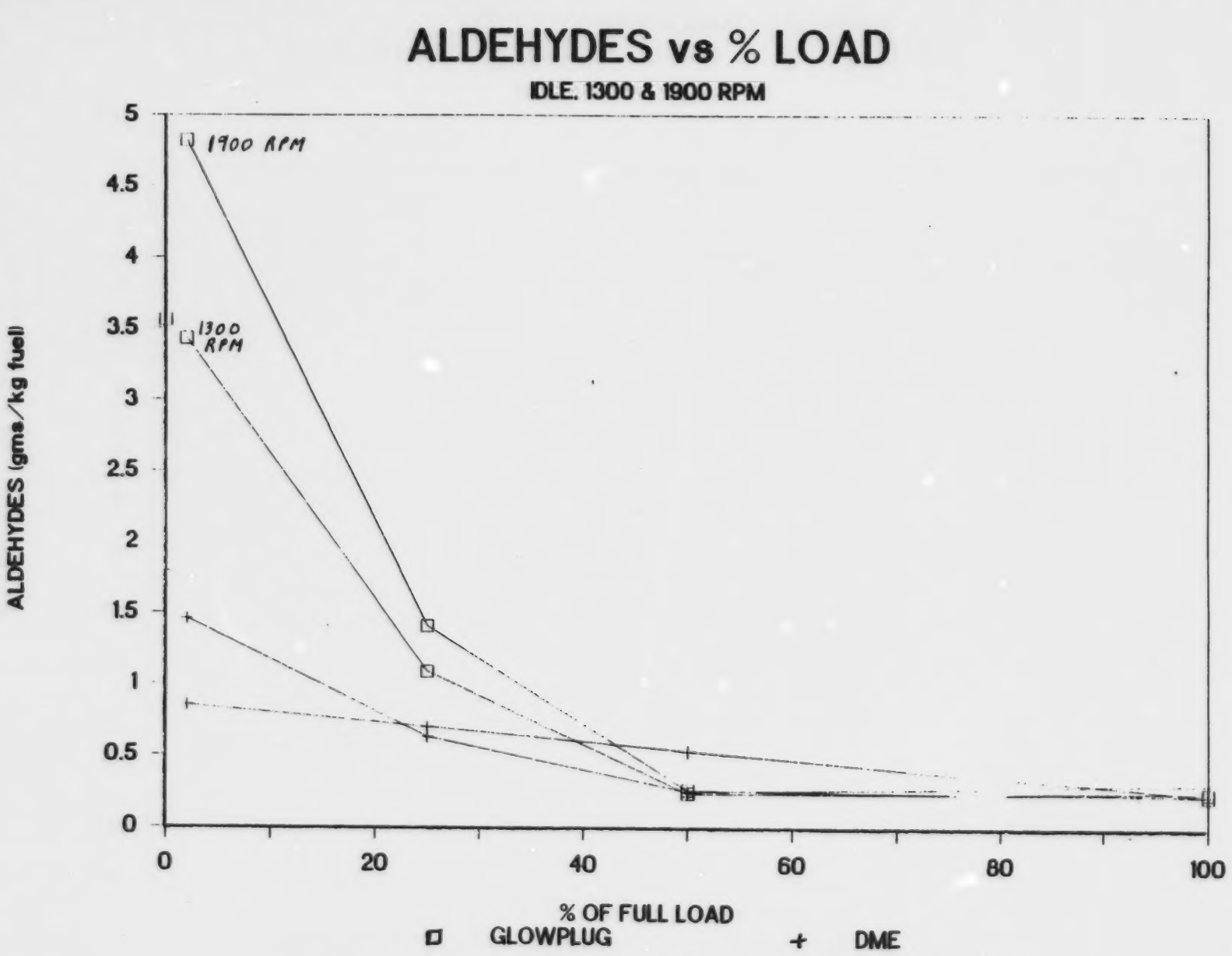

Figure 12. Aldehyde Emissions

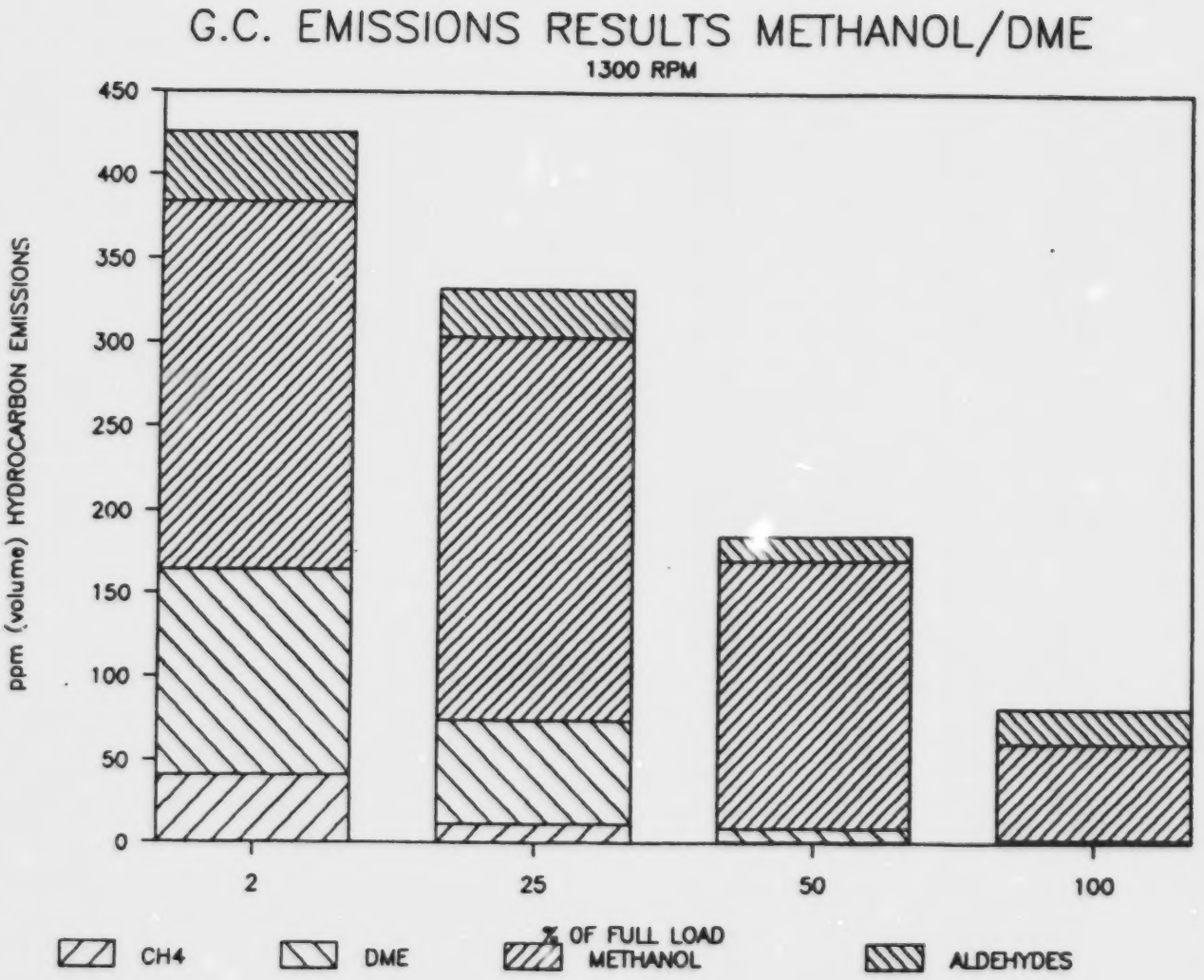

Figure 13. Hydrocarbon Emissions Fractional Makeup

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3. K.H. Kozole, J.S. Wallace, "The Use of Dimethyl Ether as a Starting Aid for Methanol-Fueled SI Engines at Low Temperatures", SAE Paper 881677.

4. S. Onishi, S. Hong Jo, K. Shoda, P. Do Jo, S. Kato, "Active Thermo-Atmosphere Combustion (ATAC) - A new Combustion Process for Internal Combustion Engines", SAE Paper 790501.

5. M.E. Karpuk, S.W. Cowley, "On-Board Dimethyl Ether Generation To Assist Methanol Engine Cold Starting", SAE Paper 881678.

Appendix 1: DME Specifications

DME Specifications	
Molecular Weight $(CH_3)_2O$	46.069
Vapour Pressure @ 20 C	530.9 kPa
Density (gas) @ 101.325 kPa, 20 C	1.918 kg/m ^{3}
Specific Heat Ratio C_p/C_v	1.11
Flammability Limits in Air	3.4% - 27% by volume
Gas Constant R	180.47 J/(K kg) Lower
Heating Value	28.808 kJ/kg

Methanol Specifications	
Molecular Weight CH_3OH	32.04
Density (liq) @ 101.325 kPa, 25 C	792 kg/m ^{3}
Flammability Limits in Air	6.0 - 36.5% by volume
Lower Heating Value	20.0 kJ/kg

Appendix 2: SAE Procedure

♦ DIESEL ENGINE EMISSION MEASUREMENT PROCEDURE—SAE J1003 FEB84

SAE Recommended Practice

Report of the Automotive Emissions Committee, approved March 1973, completely revised February 1984. Rationale statement available

1. Purpose or Scope—This SAE Recommended Practice is intended for use as a test procedure to determine the gaseous emission levels of diesel engines. Its purpose is to provide a map of an engine's emissions characteristics which, through use of the proper weighting factors, can be used as a measure of that engine's emission levels under various applications. The emission results for hydrocarbons, nitrogen oxides, carbon monoxide, and carbon dioxide are expressed in units of grams per kilowatt hour (grams/brake horsepower hour) and represent the mass rate of emissions per unit of work accomplished.

The emissions are measured in accordance with SAE Recommended Practices J177b, J215a, and J244 using non-dispersive infrared equipment for CO and CO_2, a heated flame ionization analyzer for HC, and a high performance NDIR or a chemiluminescence analyzer for NOx. All emissions are measured during steady-state engine operation. The mass rate of emissions is calculated (a) from the concentration in the exhaust gas and the exhaust flow for each mode or; (b) alternately, using a carbon balance method, from the concentration in the exhaust gas and the mass flow rate of fuel for each mode. If method (a) is used, CO_2 should be measured for data validation. The final emissions are calculated by dividing the summation of the weighted emission mass rates by the summation of the weighted brake power values for a cycle.

2. General Provisions

2.1 Definitions

2.1.1 DIESEL ENGINE—Any compression ignition engine.

2.1.2 EXHAUST EMISSION—Any substance (but normally limited to pollutants) emitted to the atmosphere from any opening downstream from the exhaust port of the combustion chamber of an engine.

2.1.3 RATED POWER—The maximum power output of an engine as stated by the manufacturer (in accordance with SAE J1349).

2.1.4 RATED SPEED—The engine speed at which the manufacturer specifies the rated power of an engine.

2.1.5 INTERMEDIATE SPEED FOR U. S. ON-HIGHWAY APPLICATIONS—The peak torque speed, when that speed occurs between 60% and 75% of rated speed. If peak torque speed is less than 60% of rated speed, intermediate speed means 60% of rated speed. If the peak torque speed is greater than 75% of rated speed, intermediate speed means 75% of rated speed.

2.1.6 PEAK TORQUE SPEED—The speed at which the engine develops maximum torque as stated by the manufacturer.

2.1.7 CURB IDLE SPEED—For heavy-duty diesel engines equipped with manual transmissions, curb idle means the manufacturer's recommended engine speed with the transmission in neutral or with the clutch disengaged. For heavy-duty diesel engines equipped with automatic transmissions, curb idle means the manufacturer's recommended engine speed with the automatic transmission in gear and the output shaft stalled.

2.1.8 DYNAMOMETER IDLE—For heavy-duty diesel engines equipped with automatic transmissions, dynamometer idle means the manufacturer's recommended engine speed without a transmission that simulates the manufacturer's recommended engine speed with a transmission and with the transmission in neutral.

2.1.9 RATED TORQUE—The maximum torque produced by an engine, as stated by the manufacturer.

2.1.10 PERCENT LOAD—The fraction of the maximum available torque at that engine speed.

2.2 Abbreviations—The abbreviations used in the recommended practice have the following meanings in both capital and lower case:

API	= American Petroleum Institute
ASTM	= American Society for Testing and Materials
α	= Atomic hydrogen/carbon ratio of the fuel (approximately 1.8 for No. 2 diesel fuel)
ϕ	= Equivalence ratio (dry), that is, dry fuel air ratio (measured)/fuel-air ratio (stoichiometric)
BARO	= Absolute barometric pressure, kPa (in Hg)
BHP	= Brake power (horsepower)
BSCO	= Brake specific carbon monoxide emissions, g/kW·h (g/bhp·h)
BSFC	= Brake specific fuel consumption, g/kW·h (g/bhp·h)
BSHC	= Brake specific hydrocarbon emissions, g/kW·h (g/bhp·h)
$BSNO_x$	= Brake specific oxides of nitrogen emissions, g/kW·h (g/bhp·h)
DCO	= CO volume concentration in exhaust, PPM (dry)
DCO_2	= CO_2 volume concentration in exhaust, percent (dry)
DHC	= Hydrocarbon volume concentration in exhaust, PPM (dry)
DKNO	= NO volume concentration in exhaust, in PPM (dry and humidity corrected)
EIP	= Absolute engine intake pressure, kPa (in Hg) = BARO–inlet restriction
f/a	= dry fuel air ratio (measured) = (f/a) wet $\left(1 + \frac{G}{1000}\right)$
G	= Humidity of the inlet air in grams of water per kilogram of dry air
K	= Water-gas equilibrium constant = 3.5
K_{NO_x}	= Humidity correction factor for oxides of nitrogen
K_w	= Wet to dry correction factor
kW	= Brake power (kilowatts)
M_c	= Atomic weight of carbon (12.011)
$(M_c + M_H)$	= Mean molecular weight of fuel per carbon atom
M_{CO}	= Molecular weight of CO (28.01)
M_f	= Mass flow rate of fuel used in engine in grams/h
M_H	= Atomic weight of hydrogen (1.008)
M_{NO_2}	= Molecular weight of nitrogen dioxide (NO_2) (46.01)
P_v	= Partial pressure of water vapor, kPa (in Hg)
T	= Temperature of inlet air, °C (°F)
W_{CO}	= Mass flow rate of CO in exhaust, grams/h
W_f	= Weighting factor of U.S. on-highway applications (0.067 for modes 1, 7, and 13 and 0.08 for all other modes)
W_{HC}	= HC volume concentration in exhaust, PPMC (wet)
W_{HC}	= Mass rate of HC in exhaust, grams/h
W_{NO_x}	= Mass rate of NOx in exhaust, grams/h
Y	= H_2O volume concentration in intake air

Where:

$$Y = \frac{P_v}{BARO\text{-}P_v}$$

3. Engine Dynamometer Test Procedure

3.1 Introduction—The test procedure consists of a prescribed sequence of engine operating conditions on an engine dynamometer with measurements of HC, NO_x, CO, and CO_2 during 13 steady-state modes with five modes at rated engine speed, five modes at an intermediate speed, and three modes at an idle speed.

3.2 Fuel Specification

3.2.1 The diesel fuels employed shall be clean and bright, with pour point and cloud point adequate for operability. The fuels may contain non-metal additives as follows: Cetane improver, metal deactivator, antioxidant, dehazer, anti-rust, pour depressant, dye, and dispersant.

3.2.2 Fuel meeting the following specifications is currently recommended in the U. S. Highway regulations. Other fuels may be used, realizing that some fuel properties affect exhaust emissions results. If a fuel having a narrower specification range is desired to minimize the effect of fuel properties, the Department of Energy 2D Emissions Reference Fuel (which was first made available in October 1979) is recommended.

Item	ASTM Test No.	Range
Cetane number	D613	42–50
Distillation range	D86	
IBP, °C (°F)		171–204 (340–400)
10% Point, °C (°F)		174–238 (400–460)
50% Point, °C (°F)		243–282 (470–540)
90% Point, °C (°F)		288–321 (550–610)
EP, °C (°F)		304–349 (580–660)
Gravity, °API	D287	33–37
Total sulfur, %	D129	0.2–0.5
Hydrocarbon composition	D1319	
Aromatics, % min		27
Paraffins, naphthenes, olefins		Remainder
Flash point, °C (°F) min	D93	54 (130)
Viscosity, m^2/s (cst)	D445	$2.0–3.2 \times 10^{-6}$ (2.0–3.2)

3.3 Instrumentation

3.3.1 Instrumentation shall be provided to measure the following engine operating data:

(a) Engine speed: rpm

(b) Torque: N·m (lb·ft)

(c) Mass fuel consumption: kg/min (lb/min)

(d) Observed barometer: kPa (in Hg)
(e) Water vapor pressure: kPa (in Hg)
(f) Intake air restriction: kPa (in H_2O)
(g) Exhaust back pressure: kPa (in Hg)
(h) Intake air temperature: °C (°F)
(i) Fuel temperature at pump inlet: °C (°F)

3.3.2 Instrumentation shall be provided to measure the engine intake air flow or exhaust flow and the concentration of CO, CO_2, NO_x, and HC in the exhaust as follows:

3.3.2.1 The determination of CO, CO_2, and NO_x concentrations shall be accomplished using sampling and analysis according to SAE J177b.

3.3.2.2 The determination of HC concentration shall be accomplished using sampling and analysis by a heated flame ionization detector method using SAE J215a.

3.3.2.3 The determination of intake air or exhaust flow shall be accomplished using SAE J244.

3.4 Test Conditions

3.4.1 The following ranges of test conditions shall be maintained during exhaust emission testing:

3.4.1.1 Intake air temperature: 25 ± 5°C (77 ± 9°F)

3.4.1.2 Barometric pressure: 100 ± 3 kPa (29.6 ± 1 in Hg)

3.4.1.3 Fuel temperature at fuel pump inlet: 37 ± 5°C (99 ± 9°F)

3.4.1.4 *Intake Restriction*—The manufacturer's published maximum limit of air cleaner restriction.

3.4.1.5 *Exhaust Restriction*—Maximum permitted by the engine manufacturer as published in the sales and service literature. The restriction shall be met within ± 0.70 kPa (± 0.2 in Hg) while the engine is operating at rated power.

3.5 Test Procedure for Exhaust Emissions

3.5.1 BREAK-IN PROCEDURE—The engine shall be run in accordance with the manufacturer's recommendation for break-in of an engine for engineering performance testing.

3.5.2 PRETEST CONDITIONING PROCEDURE—Operate the engine until emission rates have stabilized.

3.5.3 EMISSIONS MEASUREMENT PROCEDURE

3.5.3.1 Operate the engine until pressures and temperatures are stabilized. Determine the maximum torque at the rated and intermediate speeds.

3.5.3.2 Operate the engine at the following modes:

Test Segment	Mode No.	Engine Speed	Observed Torque (Percent of Maximum Observed)	Time in Mode (Minutes)		Maximum Cumulative Time (Minutes)
				Minimum	Maximum	
1	1	Curb-idle		4.5	6.0	
1	2	Intermediate	2	4.5	6.0	
1	3	do	25	4.5	6.0	
1	4	do	50	4.5	6.0	42
1	5	do	75	4.5	6.0	
1	6	do	100	4.5	6.0	
1	7	Curb-idle		4.5	6.0	
2	8	Rated	100	4.5	6.0	
2	9	do	75	4.5	6.0	
2	10	do	50	4.5	6.0	36
2	11	do	25	4.5	6.0	
2	12	do	2	4.5	6.0	
2	13	Curb-idle		4.5	6.0	

3.5.3.3 During each mode, the specified speed shall be held to within 50 rpm. Torque for each mode must be held at the specified value ± 2% of the maximum torque observed.

(a) Read and record the following modal data during the last 2 min of each mode:
(1) Observed engine torque
(2) Observed engine rpm
(3) Intake air flow
(4) Engine intake air temperature
(5) Fuel flow
(6) Engine intake humidity (need not be taken for each mode unless the inlet air is humidity conditioned).

(b) Record the following for the full time in mode:
(1) Hydrocarbon analyzer output
(2) Carbon monoxide analyzer output
(3) Carbon dioxide analyzer output (if used)
(4) Nitrogen oxides (NO + NO_2) analyzer output

3.5.4 ANALYZER OUTPUT READING

3.5.4.1 Locate the last 60 s of each mode and determine the average reading.

3.5.4.2 Determine the concentration of HC, CO, CO_2, and NO_x in each mode from the analyzer output reading (paragraph 3.5.4.1).

3.5.4.3 Convert dry concentrations to wet per SAE J177b.

4. Calculations—The test results for the emission test shall be derived through the following steps:

4.1 Calculate the mass emissions of HC, CO, and NO_x in grams/hour and the power for each mode as follows:

(a) $HC_{mass} = 0.0130 \times HC_{conc}$ (ppm carbon) × exh. mass flow (lb/min)
$HC_{mass} = 0.0287 \times HC_{conc}$ (ppm carbon) × exh. mass flow (kg/min)

(b) $CO_{mass} = 0.0263 \times CO_{conc}$ (ppm) × exh. mass flow (lb/min)
$CO_{mass} = 0.0580 \times CO_{conc}$ (ppm) × exh. mass flow (kg/min)

(c) $NO_x = 0.0432 \times NO_{x_{conc}}$ (ppm) × exh. mass flow (lb/min)
$NO_{x_{mass}} = 0.0952 \times NO_{x_{conc}}$ (ppm) × exh. mass flow (kg/min)

(d) $kW_{abs} = rpm_{eng} \times torque_{abs}$ (N·m)/9549.3
$bhp_{abs} = rpm_{eng} \times torque_{abs}$ (lb·ft)/5252.1

4.2 Calculate the weighted average brake specific emissions for a cycle with the modal data from paragraph 4.1. A weighting for an average cycle which covers on-highway heavy-duty vehicles can be represented by a weighting factor of 0.20 for the average of the idle modes and 0.08 for all other modes. Calculate the brake specific emissions for HC, CO, and NO_x as follows:

$$BSHC = \frac{\Sigma(HC_{mass} \times W_f)}{\Sigma(kW \times W_f)} \quad \frac{g}{kW \cdot h}$$

$$BSHC = \frac{\Sigma(HC_{mass} \times W_f)}{\Sigma(bhp \times W_f)} \quad \frac{g}{bhp \cdot h}$$

$$BSCO = \frac{\Sigma(CO_{mass} \times W_f)}{\Sigma(kW \times W_f)} \quad \frac{g}{kW \cdot h}$$

$$BSCO = \frac{\Sigma(CO_{mass} \times W_f)}{\Sigma(bhp \times W_f)} \quad \frac{g}{bhp \cdot h}$$

$$BSNO_x = \frac{\Sigma(NO_{x_{mass}} \times W_f)}{\Sigma(kW \times W_f)} \quad \frac{g}{kW \cdot h}$$

$$BSNO_x = \frac{\Sigma(NO_{x_{mass}} \times W_f)}{\Sigma(bhp \times W_f)} \quad \frac{g}{bhp \cdot h}$$

5. Alternate Calculations

5.1 Determine the exhaust species volume concentration for each mode.

5.2 Convert wet basis measurements to a dry basis by the following:

Dry concentration = (K_w) × Wet concentration

K_w is defined as follows:

$$K_w = 1 + \left[\frac{a\left(\frac{DCO_2}{10^2} + \frac{DCO}{10^6} + \frac{2Y}{\phi}\left(\frac{DCO_2}{10^2} + \frac{DCO}{10^6} + \frac{Whc}{10^6}\right)\right)\left(1 + \frac{a}{4}\right)}{2\left(1 + \frac{\frac{DCO}{10^6}}{\left(\frac{DCO_2}{10^2}\right)K}\right)} \right]$$

5.2.1 Calculate ϕ using the measured (f/a) entering the combustion chamber. If applicable, bleed air, etc., must be subtracted from the measured air flow.

5.2.2 Calculate a separate Y value for each test segment from the pretest segment data. Apply the Y value to the K_w equation for the entire test segment.

5.3 Compute the dry (f/a) as follows:

$$(f/a) = \frac{4.77\left(1 + \frac{a}{4}\right)(f/a)_{stoich}}{\frac{1}{\overline{X}} - \left(\frac{DCO}{2\overline{X}10^6}\right) - \left(\frac{DHC}{\overline{X}10^6}\right) + \frac{a}{4}\left(1 - \frac{DHC}{\overline{X}10^6}\right) - \frac{0.75a}{\left(\frac{K}{\frac{DCO}{\overline{X}10^6}}\right) + \left(\frac{1-K}{1 - \frac{DHC}{\overline{X}10^6}}\right)}}$$

$$(f/a)_{stoich} = \frac{M_f + aM_a}{138.18\left(1 + \frac{a}{4}\right)}$$

$$\overline{X} = \frac{DCO_2}{10^2} + \frac{DCO}{10^6} + \frac{DHC}{10^6}$$

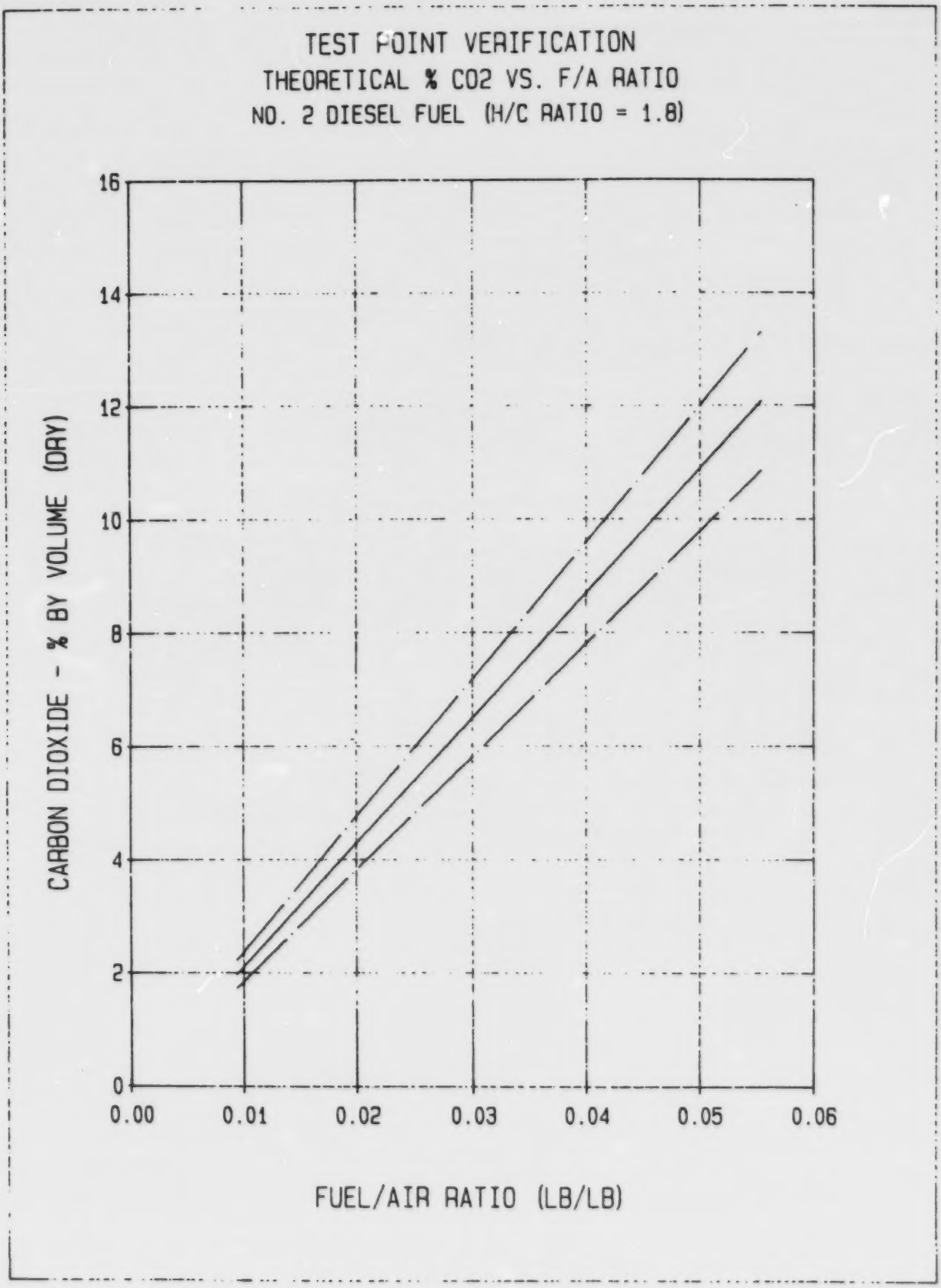
TEST POINT VERIFICATION
THEORETICAL % CO2 VS. F/A RATIO
NO. 2 DIESEL FUEL (H/C RATIO = 1.8)
CARBON DIOXIDE - % BY VOLUME (DRY)
16
14
12
10
8
6
4
2
0
0.00
0.01
0.02
0.03
0.04
0.05
0.06
FUEL/AIR RATIO (LB/LB)

FIG. 1

5.4 Multiply the dry nitric oxide volume concentration by the following humidity correction factor to obtain DKNO:

$$K_{NO_x} = \frac{1}{1 + A\,(G - 10.7) + B\,(T - 29.5)}$$

Where:

$A = 0.308\ (f/a) - 0.0266$
$B = 0.209\ (f/a) + 0.00954$
T = temperature of inlet air, °C
G = g H_2O/kg dry air

$$K_{NO_x} = \frac{1}{1 + A\,(G - 75) + B\,(T - 85)}$$

Where:

$A = 0.044\ (f/a) - 0.0038$
$B = 0.116\ (f/a) + 0.0053$
T = temperature of inlet air, °F
G = grains H_2O/lb of dry air

5.5 Calculate the mass emissions of each species in grams/hour for each mode as follows:

$$HC\ g/h = W_{HC} = \frac{(DHC/10^4)\,M_f}{(DCO/10^4) + DCO_2 + (DHC/10^4)}$$

$$CO\ g/h = W_{CO} = \frac{M_{CO}(DCO/10^4)\,M_f}{(M_e + \alpha\,M_H)\,[(DCO/10^4) + DCO_2 + (DHC/10^4)]}$$

$$NO_x\ g/h = W_{NO_x} = \frac{M_{NO_2}\,(DKNO_x/10^4)\,M_f}{(M_e + \alpha\,M_H)\,[(DCO/10^4) + DCO_2 + (DHC/10^4)]}$$

5.6 Weight the values of kW, W_{HC}, W_{CO}, W_{NO_x} as defined in paragraph 4.2.

5.7 Calculate the brake specific emissions for each test by summing the weighted values kW, W_{HC}, W_{CO}, and W_{NO_x} for each mode as follows:

$$BSHC = \frac{\Sigma\ \text{weighted}\ W_{HC}}{\Sigma\ \text{weighted kW}}$$

$$BSCO = \frac{\Sigma\ \text{weighted}\ W_{CO}}{\Sigma\ \text{weighted kW}}$$

$$BSNO_x = \frac{\Sigma\ \text{weighted}\ W_{NO_x}}{\Sigma\ \text{weighted kW}}$$

6. ***Data Validation***—It is a good practice to evaluate the data to detect leaks in the engine air intake system and gaseous emissions sampling system. This can be done in the following way which requires the measurement of both CO_2 and air flow during the test:

Compute the measured fuel : air ratio and dry CO_2. The point defined by those coordinates on the data validation curve shown in Fig. 1 should fall between the dashed lines. If the data falls outside the dashed lines, the test should be repeated.

7. Appendices—Table A-1 shows some alternative weighting factors that have been proposed for European and off-highway use. Also shown for informational purposes is the Japanese heavy-duty diesel cycle.

TABLE A-1—GASEOUS EMISSIONS TEST CYCLE MODES AND WEIGHTING FACTORS

	Engine		Weighting Factors (%)			Japanese H. D. Diesel*		
						Engine		
Mode No.	Speed	Load (%)	U.S.E.P.A.	Proposed ECE 24 G.R.P.A.	Proposed E.M.A. Off-Highway	Speed (% of Rate)	Load	Weighting Factor (%)
1	Idle	—	20/3	25/3	5	Idle	—	3.5
2	Intermediate	2	8	8 (2–5% load)	5	0.4 or	100	7.1
3	"	25	8	8	5	1000 rpm	25	5.9
4	"	50	8	8	10	0.6	100	10.7
5	"	75	8	8	5	0.6	25	12.2
6	"	100	8		5	0.8	75	28.6
7	Idle	—	20/3	25/3	5			
8	Rated	100	8	10	20			
9	"	75	8	2	15			
10	"	50	8	2	10			
11	"	25	8	2	5			
12	"	2	8	2 (2–5% load)	5			
13	Idle	—	20/3	25/3	5			

* Wet-to-dry and humidity correction factors as follows:
W/D, $K = 1 - 1.9^*\ F/A$
HUM, $K = 1/(1 - 0.0025(H - 75))$

Appendix 3: Test Results

NOTES ON METHANOL SINGLE CYLINDER ENGINE TESTS

TEST #3

NOVEMBER 28, 1989
13 MODE WITH GLOW PLUG ASSIST (12 amps)

This test was a preliminary run to assure the equipment and procedures were adequate. In this test, and all following tests, the timing was kept constant at .130 inch static injection timing. This timing yields a range of beginning of injection marks from 8 degrees ATDC at idle to 12 degrees BTCD at full load. End of injection remains almost constant at 28 degrees ATDC.

The emissions calculations have been corrected for the molecular weight of methanol. The lower heating value of methanol (20,000 kJ/kg) was used for efficiency rates. The hydrocarbon readings have not been adjusted for the sensitivity factor of the FID to methanol. Emissions calculations were done on a dry basis. Air flow values have not been corrected for ambient pressure variations.

It should be noted that these results are from steady state tests on a single cylinder engine. The high friction of the engine results is skewed values and therefore this data should not be compared with other engine results. The tests should be viewed on a strictly comparative basis.

TEST #3 METHANOL 13 MODE GLOW PLUG ASSIST (12 AMPS)

DATE	NOV 28/89						
	#1	#2	#3	#4	#5	#6	#7
SPEED (rpm)	830	1290	1300	1302	1301	1300	830
TORQUE (ftlbf)	1.4	7	26	52.5	78.8	104	1
% FULL LOAD @ THIS SPEED	0%	2%	25%	50%	75%	100%	0%
BRAKE HP (raw)	0.2	1.7	6.4	13.0	19.5	25.7	0.2
BSFC (lbm/HP hr)	21.352	4.663	1.701	1.109	1.016	0.976	27.746
EFFICENCY	1.4	6.3	17.4	26.7	29.1	30.3	1.1
PHI	0.30	0.32	0.43	0.42	0.46	0.52	0.12
PEAK PRESSURE (psi)	646	708	728	1185	1631	2098	636
PEAK PRES. AT (deg ATDC)	18	17	19	7	7	4	0
dP/dt (psi/deg)	25	48	55	107	165	162	21
IGNITION DELAY (deg CA)	14	12	15	10	9	8	14
FUEL FLOW (gm/s)	0.60	1.01	1.38	1.82	2.50	3.17	0.55
FUEL IN PRESS (% OF 250 psi)	5.2	9.1	11.2	20.9	32.8	51	4.3
FUEL IN PRESS (psi)	13	22.75	28	52.25	82	127.5	10.75
FUEL OUT TEMP (c)	51	49	49	48	48	49	50
AIR FLOW (cfm)	22.2	35.8	35.5	49.0	61.0	68.1	51.4
AIR FLOW (gm/s)	12.8	20.7	20.5	28.3	35.3	39.4	29.7
IN. AIR PRESS (in. H2O)	0.3	0.5	0.6	0.8	1.1	1.3	0.2
BOOST (volts)	1.513	1.552	1.556	1.942	2.374	2.729	1.512
BOOST (psi)	0.59	0.98	1.02	4.88	9.2	12.75	0.58
IN MANIFOLD AIR TEMP (c)	45	47	48	51	63	80	79
EXHAUST BACK PRESS (psi)	0.5	0.5	1	2.2	3.6	5.8	0.1
EXHAUST TEMP (c)	160	252	349	374	420	513	212
COOLANT IN TEMP (c)	51	53	47	50	46	48	51
COOLANT OUT TEMP (c)	54	58	53	58	58	62	54
OIL PRESS (psi)	58	54	53	51	48	42	45
OIL TEMP (c)	70	71	71	75	78	89	89
Q1 STORAGE	100	102	104	106	108	110	112
Q2 STORAGE	101	103	105	107	109	111	114

	#8	#9	#10	#11	#12	#13
SPEED (rpm)	1895	1900	1900	1903	1904	825
TORQUE (ftlbf)	4	18	35	54	71.2	1
% FULL LOAD @ THIS SPEED	2%	25%	50%	75%	100%	0%
BRAKE HP (raw)	1.4	6.5	12.7	19.6	25.8	0.2
BSFC (lbm/HP hr)	10.197	2.593	1.315	1.214	1.157	30.437
EFFICENCY	2.9	11.4	22.5	24.4	25.6	1.0
PHI	0.65	0.42	0.35	0.42	0.47	0.31
PEAK PRESSURE (psi)	665	779	1045	1512	1772	638
PEAK PRES. AT (deg ATDC)	18	19	15	4	3	-1
dP/dt (psi/deg)	29	30	118	155	174	22
IGNITION DELAY (deg CA)	10-15-20	11-19	12	8	8	11
FUEL FLOW (gm/s)	1.85	2.13	2.10	2.99	3.76	0.60
FUEL IN PRESS (% OF 250 psi)	17.1	21.6	27.3	44.7	68.3	4.2
FUEL IN PRESS (psi)	42.75	54	68.25	111.75	170.75	10.5
FUEL OUT TEMP (c)	56	58	59	61	62	66
AIR FLOW (cfm)	46.5	56.7	67.8	79.4	89.0	21.5
AIR FLOW (gm/s)	26.9	32.8	39.2	45.9	51.5	12.4
IN. AIR PRESS (in. H2O)	0.7	1.1	1.3	1.6	2.2	0.3
BOOST (volts)	1.577	1.818	2.097	2.459	2.757	1.514
BOOST (psi)	1.23	3.64	6.43	10.05	13.03	0.6
IN MANIFOLD AIR TEMP (c)	68	65	67	75	90	82
EXHAUST BACK PRESS (psi)	1	2	3	6	8.7	0.15
EXHAUST TEMP (c)	413	425	415	458	515	220
COOLANT IN TEMP (c)	45	48	47	46	45	48
COOLANT OUT TEMP (c)	54	60	58	62	63	53
OIL PRESS (psi)	41.5	38.9	36.2	33.3	30	39.6
OIL TEMP (c)	84	91	97	103	110	99
Q1 STORAGE	115	117	119	121	123	125
Q2 STORAGE	116	118	120	122	124	126

WET BULB 11.3 DRY BULB 21 ATM PRES. 29.59

INJECTOR/CAM: 9-10-250/F1419 PRESS. TRANS: 380 PSI/VOLT

TEST #3 — METHANOL 13 MODE GLOW PLUG ASSIST (12 AMPS)

DATE — NOV 28/89

gm H2O/Kg AIR (.1429xgrains)	2.14		
PART. PRES. H20 IN AIR (inHg)	0.203	H20 P. SAT.(KPa)	1.335586
H20 VOL. CONC. IN INTAKE AIR	0.007	INT. CONSTANT	0.000371
F/A (stoich)	0.155		
H/C RATIO	4	FUEL MOL. WEIGHT	32.04
WATER-GAS EQU. CONSTANT	3.5		

	#1	#2	#3	#4	#5	#6	#7
EXHAUST (Kg/min)	0.81	1.30	1.31	1.81	2.27	2.55	1.82
F/A (dry)	0.046	0.049	0.067	0.064	0.071	0.080	0.019
PHI	0.301	0.316	0.435	0.415	0.458	0.520	0.120
SPECIES WET (ppm)							
NOx	72	85	156	306	499	675	77
THC	8127	6653	1305	158	129	149	7191
WET to DRY C.F.	1.051	1.073	1.106	1.121	1.134	1.155	1.048
SPECIES DRY (ppm carbon)							
CO	1723	2217	1443	118	128	266	1396
CO2%	2.55	3.79	5.8	6.89	7.73	9.16	2.44
NOx	80	98	203	397	679	985	76
THC	8539	7140	1443	177	146	172	7538
MASS FLOW (gm/hr)							
CO	90.22	149.09	102.84	9.75	12.98	28.79	72.79
CO2%	2098	4005	6496	8950	12316	15581	1999
NOx	7	11	24	56	113	175	6
THC	512	549	118	17	17	21	450
BS EMMISIONS (gm/hp.hr)							
CO	N.A.	N.A.	16.0	0.7	0.7	1.1	N.A.
CO2%	N.A.	N.A.	1009.4	687.7	630.9	605.3	N.A.
NOx	N.A.	N.A.	3.7	4.1	5.8	6.8	N.A.
THC	N.A.	N.A.	18.3	1.3	0.9	0.8	N.A.
MASS SPECIFIC (g/Kg)							
CO	42.10	41.00	20.71	1.49	1.44	2.53	36.60
CO2%	979.21	1101.38	1308.19	1367.43	1368.43	1366.75	1005.21
NOx	3.23	2.98	4.78	8.24	12.56	15.36	3.27
THC	238.77	151.08	23.70	2.56	1.89	1.87	226.14

	#8	#9	#10	#11	#12	#13
EXHAUST (Kg/min)	1.72	2.10	2.48	2.93	3.31	0.78
F/A (dry)	0.069	0.065	0.054	0.065	0.073	0.048
PHI	0.447	0.420	0.346	0.422	0.473	0.313
SPECIES WET (ppm)						
NOx	115	150	316	178	455	68
THC	6392	3580	219	149	166	4711
WET to DRY C.F.	1.103	1.110	1.114	1.129	1.144	1.046
SPECIES DRY (ppm carbon)						
CO	2413	3215	298	154	176	1113
CO2%	5.59	5.98	6.39	7.37	8.37	2.32
NOx	151	194	387	234	631	76
THC	7052	3975	244	168	190	4927
MASS FLOW (gm/hr)						
CO	215.36	321.25	30.52	19.58	24.49	72.14
CO2%	7840	9390	10284	14728	18516	2363
NOx	22	32	65	49	146	8
THC	720	455	29	24	31	365
BS EMMISIONS (gm/hp.hr)						
CO	N.A.	N.A.	4.7	1.5	1.3	2.8
CO2%	N.A.	N.A.	1598.0	1131.6	948.5	91.8
NOx	N.A.	N.A.	10.1	3.8	7.5	0.3
THC	N.A.	N.A.	4.4	1.9	1.6	14.2
MASS SPECIFIC (g/Kg)						
CO	32.26	41.94	4.04	1.82	1.81	33.27
CO2%	1174.42	1225.88	1361.74	1367.31	1367.34	1089.62
NOx	3.31	4.15	8.61	4.54	10.78	3.74
THC	107.89	59.36	3.78	2.27	2.26	168.49

13 MODE TOTALS

CO	8.36	NOx	5.33
CO2%	854.11	THC	23.23

NOTES ON METHANOL SINGLE CYLINDER ENGINE TESTS

TEST #4

NOVEMBER 28, 1989
13 MODE WITH GLOW PLUG ASSIST (12 amps)

This test was the baseline methanol emissions run to compare all subsequent results against. In this test, and all following tests, the timing was kept constant at .130 inch static injection timing. This timing yields a range of beginning of injection marks from 8 degrees ATDC at idle to 12 degrees BTDC at full load. End of injection remains almost constant at 28 degrees ATDC.

The emissions calculations have been corrected for the molecular weight of methanol. The lower heating value of methanol (20,000 kJ/kg) was used for efficiency rates. The hydrocarbon readings have not been adjusted for the sensitivity factor of the FID to methanol. Emissions calculations were done on a dry basis. Air flow values have not been corrected for ambient pressure variations.

It should be noted that these results are from steady state tests on a single cylinder engine. The high friction of the engine results in skewed values and therefore this data should not be compared with other engine results. The tests should be viewed on a strictly comparative basis.

TEST #4 — METHANOL 13 MODE GLOW PLUG ASSIST (12 AMPS)

DATE — NOV 28/89 — RUN TWO AT 6:30 PM

	#1	#2	#3	#4	#5	#6	#7
SPEED (rpm)	850	1290	1304	1303	1301	1300	832
TORQUE (ftlbf)	1	7	28	53.2	79	104.5	1
% FULL LOAD @ THIS SPEED	0%	2%	25%	50%	75%	100%	0%
BRAKE HP (raw)	0.2	1.7	7.0	13.2	19.6	25.9	0.2
BSFC (lbm/HP hr)	27.244	4.763	1.476	1.084	0.966	0.959	27.833
EFFICENCY	1.1	6.2	20.0	27.3	30.6	30.9	1.1
PHI	0.29	0.34	0.38	0.41	0.43	0.52	0.29
PEAK PRESSURE (psi)	640	683	661	1185	1620	2098	635
PEAK PRES. AT (deg ATDC)	-1	0	19	9	8	5	-1
dP/dt (psi/deg)	21	22	24	87	102	190	22
IGNITION DELAY (deg CA)	21	21	17	11	9	8	19
FUEL FLOW (gm/s)	0.56	1.03	1.29	1.80	2.38	3.13	0.56
FUEL IN PRESS (% OF 250 psi)	4.1	8.5	11.5	20.9	32	49.6	4.3
FUEL IN PRESS (psi)	10.25	21.25	28.75	52.25	80	124	10.75
FUEL OUT TEMP (c)	59	54	52	50	49	50	59
AIR FLOW (cfm)	21.5	33.8	37.8	49.4	62.4	67.7	21.6
AIR FLOW (gm/s)	12.4	19.5	21.9	28.6	36.1	39.2	12.5
IN. AIR PRESS (in. H2O)	0.3	0.45	0.6	0.8	1.1	1.3	0.2
BOOST (volts)	1.518	1.521	1.609	1.958	2.405	2.71	1.516
BOOST (psi)	0.64	0.67	1.55	5.04	9.51	12.56	0.62
IN MANIFOLD AIR TEMP (c)	78	58	53	55	65	80	75
EXHAUST BACK PRESS (psi)	0.1	0.5	0.9	2.2	3.6	6	0.14
EXHAUST TEMP (c)	224	257	337	377	412	520	215
COOLANT IN TEMP (c)	49	46	51	51	46	44	51
COOLANT OUT TEMP (c)	53	53	59	60	57	59	54
OIL PRESS (psi)	49	50	49	48	45	41	45
OIL TEMP (c)	80	75	77	77	82	90	89
Q1 STORAGE	100	102	104	106	108	110	112
Q2 STORAGE	101	103	105	107	109	111	113

	#8	#9	#10	#11	#12	#13
SPEED (rpm)	1896	1903	1903	1902	1902	830
TORQUE (ftlbf)	5	17.4	35	54	71.8	1
% FULL LOAD @ THIS SPEED	2%	25%	50%	75%	100%	0%
BRAKE HP (raw)	1.8	6.3	12.7	19.6	26.0	0.2
BSFC (lbm/HP hr)	8.244	2.630	1.478	1.221	1.110	31.225
EFFICENCY	3.6	11.2	20.0	24.2	26.7	0.9
PHI	0.47	0.44	0.39	0.43	0.46	0.33
PEAK PRESSURE (psi)	654	500	868	1403	1731	642
PEAK PRES. AT (deg ATDC)	0	23	18	8	7	0
dP/dt (psi/deg)	22	26	30	103	106	22
IGNITION DELAY (deg CA)	22	21	15	9	8	12
FUEL FLOW (gm/s)	1.88	2.09	2.36	3.01	3.64	0.62
FUEL IN PRESS (% OF 250 psi)	15.8	20.7	27.2	43.6	66	3.9
FUEL IN PRESS (psi)	39.5	51.75	68	109	165	9.75
FUEL OUT TEMP (c)	57	59	59	60	60	66
AIR FLOW (cfm)	44.6	53.2	68.2	78.5	89.2	21.2
AIR FLOW (gm/s)	25.8	30.8	39.4	45.4	51.6	12.3
IN. AIR PRESS (in. H2O)	0.7	0.9	1.3	1.7	2.1	0.3
BOOST (volts)	1.54	1.74	2.104	2.44	2.769	1.519
BOOST (psi)	0.86	2.86	6.5	9.86	13.15	0.65
IN MANIFOLD AIR TEMP (c)	65	62	65	76	89	82
EXHAUST BACK PRESS (psi)	0.9	2	3	6.1	8.8	0.1
EXHAUST TEMP (c)	414	462	418	462	515	220
COOLANT IN TEMP (c)	43	47	46	46	45	49
COOLANT OUT TEMP (c)	54	59	58	61	63	53
OIL PRESS (psi)	40	39.5	37	33	31	38
OIL TEMP (c)	88	88	95	103	108	103
Q1 STORAGE	114	116	118	120	122	124
Q2 STORAGE	115	117	119	121	123	125

WET BULB 11.3 DRY BULB 24 ATM. PRES 29.69

INJECTOR/CAM: 9-10-250/F1419
PRESS. TRANS: 380 PSI/VOLT

TEST #4

DATE

METHANOL 13 MODE GLOW PLUG ASSIST (12 AMPS)

NOV 28/89 RUN TWO AT 6:30 PM

gm H2O/Kg AIR (.1429xgrains)	2.14		
PART. PRES. H2O IN AIR (inHg)	0.143	H20 P. SAT.(KPa)	1.335586
H20 VOL. CONC. IN INTAKE AIR	0.005	INT. CONSTANT	0.000371
F/A (stoich)	0.155		
H/C RATIO	4	FUEL MOL. WEIGHT	32.04
WATER-GAS EQU. CONSTANT	3.5		

	#1	#2	#3	#4	#5	#6	#7
EXHAUST (Kg/min)	0.78	1.23	1.39	1.82	2.31	2.54	0.78
F/A (dry)	0.045	0.053	0.059	0.063	0.066	0.080	0.044
PHI	0.29	0.34	0.38	0.41	0.43	0.52	0.29
SPECIES WET (ppm)							
NOx	73	95	188	330	505	690	63
THC	7454	7259	1146	175	156	141	1541
WET to DRY C.F.	1.048	1.067	1.100	1.121	1.131	1.159	1.047
SPECIES DRY (ppm carbon)							
CO	1502	2111	1311	99	99	238	1541
CO2%	2.39	3.43	5.48	6.85	7.53	9.46	2.38
NOx	76	104	217	395	617	916	66
THC	7808	7744	1261	196	176	163	1614
MASS FLOW (gm/hr)							
CO	79.05	155.19	92.96	8.16	9.81	24.63	99.92
CO2%	1977	3962	6106	8877	11728	15384	2425
NOx	7	13	25	54	100	156	7
THC	470	651	102	19	20	19	120
BS EMMISIONS (gm/hp.hr)							
CO	N.A.	N.A.	13.4	0.6	0.5	1.0	N.A.
CO2%	N.A.	N.A.	878.3	672.6	599.3	594.8	N.A.
NOx	N.A.	N.A.	3.6	4.1	5.1	6.0	N.A.
THC	N.A.	N.A.	14.7	1.4	1.0	0.7	N.A.
MASS SPECIFIC (g/Kg)							
CO	39.52	41.78	19.97	1.26	1.14	2.19	49.96
CO2%	988.29	1066.78	1311.72	1367.39	1368.28	1367.48	1212.54
NOx	3.30	3.38	5.44	8.24	11.72	13.85	3.49
THC	235.12	175.38	21.98	2.85	2.33	1.72	59.88

	#8	#9	#10	#11	#12	#13
EXHAUST (Kg/min)	1.66	1.97	2.51	2.90	3.31	0.77
F/A (dry)	0.073	0.068	0.060	0.066	0.070	0.051
PHI	0.47	0.44	0.39	0.43	0.46	0.33
SPECIES WET (ppm)						
NOx	104	131	265	326	446	77
THC	6066	3406	330	158	174	6466
WET to DRY C.F.	1.107	1.113	1.113	1.130	1.143	1.047
SPECIES DRY (ppm carbon)						
CO	2413	2386	538	143	148	1277
CO2%	5.81	6.17	6.3	7.44	8.34	2.35
NOx	128	159	311	398	561	82
THC	6714	3789	367	178	199	6767
MASS FLOW (gm/hr)						
CO	211.73	231.09	62.57	18.11	20.22	79.19
CO2%	8021	9402	11527	14823	17925	2293
NOx	18	25	59	83	126	8
THC	674	420	49	26	31	480
BS EMMISIONS (gm/hp.hr)						
CO	N.A.	N.A.	9.0	1.4	1.0	3.1
CO2%	N.A.	N.A.	1658.1	1123.1	916.0	88.6
NOx	N.A.	N.A.	8.5	6.3	6.4	0.3
THC	N.A.	N.A.	7.0	2.0	1.6	18.6
MASS SPECIFIC (g/Kg)						
CO	31.37	30.72	7.36	1.67	1.54	35.38
CO2%	1188.32	1249.90	1355.53	1369.08	1369.30	1024.37
NOx	2.73	3.36	6.98	7.65	9.62	3.73
THC	99.87	55.83	5.74	2.39	2.38	214.52

13 MODE TOTALS

CO	7.83	NOx	5.06
CO2%	845.45	THC	21.66

NOTES ON METHANOL SINGLE CYLINDER ENGINE TESTS

TEST #5

DECEMBER 7-13, 1989
DME SUBSTITUTION TEST MAP NO GLOW PLUG

This test was to determine what amount of DME was required at various speeds and loads to yield stable firing of the engine. At each speed/load point the various levels of DME were introduced into the engine. The DME level would first be set then the methanol fuel rate would be reduced to return the torque to the standard setting. The timing was kept constant at .130 inch static injection timing. This timing yields a range of beginning of injection marks from 8 degrees ATDC at idle to 12 degrees BTDC at full load. End of injection remains almost constant at 28 degrees ATDC.

No emissions testing was done at this stage.

It should be noted that these results are from steady state tests on a single cylinder engine. The high friction of the engine results in skewed values and therefore this data should not be compared with other engine results. The tests should be viewed on a strictly comparative basis.

TEST #5 **DME SUBSTITUTION TEST MAP NO GLOW PLUG**

DATE	DEC 13/89			DEC 12/89 2 PM							
	1	2	3	4	5	6	7	8	9	10	11
SPEED (rpm)	820	825	820	1200	1300	1300	1300	1900	1900	1900	1900
TORQUE (ftlbf)	2.4	2.4	2.4	1.5	2.2	2.2	2.2	2.4	5	4	2.6
			*			*	*		*	*	*
% FULL LOAD @ THIS SPEED	IDLE	IDLE	IDLE	2%	2%	2%	2%	2%	2%	2%	2%
BRAKE HP (raw)	0.4	0.4	0.4	0.3	0.5	0.5	0.5	0.9	1.8	1.4	0.9
BSFC (lbm/HP hr)	14.247	4.924	2.118	25.010	8.453	6.121	5.830	13.965	4.388	5.174	6.392
EFFICENCY	1.9	3.6	3.7	1.1	2.7	3.1	3.0	1.8	5.1	4.1	3.0
DME % ENERGY	8	40	74	5	24	36	41	17	25	29	36
DME % MASS	6	31	66	4	18	28	33	12	19	22	28
PHI DME	0.03	0.07	0.13	0.02	0.06	0.07	0.08	0.07	0.08	0.09	0.10
PHI METHANOL	0.31	0.11	0.05	0.38	0.18	0.13	0.12	0.37	0.24	0.23	0.18
PHI COMBINED	0.33	0.18	0.18	0.41	0.24	0.20	0.21	0.44	0.32	0.32	0.28
PEAK PRESSURE (psi)	666	790	960	707	817	877	850	734	776	804	822
PEAK PRESS. AT (deg ATDC	0	0	1	1	0	0	0	0	0	-1	-2
dP/dt (psi/deg)	22	32	60	24	28	43	34	27	39	48	49
IGNITION DELAY (deg)	14	12	0	17	15	13	11	12	12	10	8
FUEL FLOW (gm/s)	0.67	0.23	0.10	1.08	0.58	0.42	0.40	1.53	1.00	0.94	0.76
FUEL IN PRESS (read)	5.5	3	3.3	10.9	4.7	4.2	4	12.3	8.8	8	7.3
FUEL IN PRESS (psi)	13.75	7.5	8.25	27.25	11.75	10.5	10	30.75	22	20	18.25
FUEL OUT TEMP (c)	40	49	51	44	53	54	54	54	54	55	57
DME FLOW (volts)	0.35	0.85	1.5	0.36	1	1.25	1.5	1.61	1.75	2	2.26
DME MASSFLOW (g/s)	0.040	0.107	0.195	0.041	0.128	0.161	0.195	0.210	0.229	0.262	0.297
DME PRESSURE (KPa)	283	316	278	333	332	327	325	328	330	327	323
AIR FLOW (cfm)	24.6	24.1	23.2	31.4	35.8	36.0	36.4	46.5	46.2	46.1	46.0
AIR FLOW (gm/s)	14.2	13.9	13.4	18.2	20.7	20.8	21.1	26.9	26.7	26.7	26.6
IN. AIR PRESS (in. H2O)	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7
BOOST (volts)	1.52	1.52	1.52	1.56	1.56	1.56	1.56	1.58	1.58	1.58	1.58
BOOST (psi)	0.66	0.66	0.66	1.06	1.06	1.06	1.06	1.26	1.26	1.26	1.26
IN MANIFOLD AIR TEMP (c)	34	36	37	54	49	47	47	52	50	51	52
EXHAUST BACK PRESS (psi)	0.19	0.19	0.19	0.52	0.51	0.47	0.48	0.8	0.97	0.94	0.91
EXHAUST TEMP (c)	158	145	145	231	207	199	202	320	321	310	299
COOLANT IN TEMP (c)	52	54	50	50	54	54	54	49	46	47	48
COOLANT OUT TEMP (c)	53	55	52	53	57	57	57	57	55	55	55
OIL PRESS (psi)	76.8	72.3	68.5	42.6	38.7	37.7	37.9	31.2	32.8	32.1	31.3
OIL TEMP (c)	56	61	64	66	73	75	74	83	78	80	83
AMB. TEMP (c)	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
WET BULB TEMP	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATM. PRESS (in Hg)	29.58	29.58	29.58	29.58	29.58	29.58	29.58	29.58	29.58	29.58	29.58

* means stable operation
INJECTOR/CAM: 9-10-250/F1419
PRESS. TRANS: 380 PSI/VOLT

TEST #5 DME SUBSTITUTION TEST MAP NO GLOW PLUG

DATE	DEC 7/89 2 PM				DEC 8/89 3 PM				
	13	14	15	16	17	18	19	20	20.1
SPEED (rpm)	1300	1300	1300	1300	1900	1900	1900	1900	1900
TORQUE (ftlbf)	28	28	27	27.2	19	18	18.5	19	19.5
		*	*	*				*	*
% FULL LOAD @ THIS SPEED	25%	25%	25%	25%	25%	25%	25%	25%	25%
BRAKE HP (raw)	6.9	6.9	6.7	6.7	6.9	6.5	6.7	6.9	7.1
BSFC (lbm/HP hr)	1.420	1.262	1.153	1.102	3.233	3.047	2.419	1.716	1.534
EFFICENCY	19.9	21.7	22.2	20.4	9.0	9.4	11.4	14.5	15.0
DME % ENERGY	5	7	14	24	2	4	7	16	22
DME % MASS	3	5	10	18	1	3	5	12	16
PHI DME	0.02	0.02	0.04	0.08	0.01	0.02	0.03	0.06	0.08
PHI METHANOL	0.36	0.32	0.28	0.27	0.57	0.51	0.42	0.30	0.28
PHI COMBINED	0.38	0.34	0.32	0.36	0.59	0.53	0.45	0.36	0.36
PEAK PRESSURE (psi)	870	870	903	983	781	909	720	885	946
PEAK PRESS. AT (deg ATDC	13	11	5	2	0	22	19	7	3
dP/dt (psi/deg)	27	28	32	51	27	110	28	39	56
IGNITION DELAY (deg)	10	8	6	4	15	20	15	6	4
FUEL FLOW (gm/s)	1.24	1.10	0.97	0.93	2.80	2.50	2.04	1.49	1.36
FUEL IN PRESS (read)	9.4	9.5	8.9	7.7	30.5	25	19	13.6	12.6
FUEL IN PRESS (psi)	23.5	23.75	22.25	19.25	76.25	62.5	47.5	34	31.5
FUEL OUT TEMP (c)	49	50	51	53	49	51	55	60	63
DME FLOW (volts)	0.36	0.51	0.84	1.57	0.36	0.53	0.84	1.5	2.05
DME MASSFLOW (g/s)	0.041	0.062	0.106	0.204	0.041	0.064	0.106	0.195	0.269
DME PRESSURE (KPa)	368	363	362	356	334	330	327	327	328
AIR FLOW (cfm)	38.6	38.7	38.5	38.3	54.6	54.8	54.8	54.6	54.6
AIR FLOW (gm/s)	22.3	22.4	22.3	22.2	31.6	31.7	31.7	31.6	31.6
IN. AIR PRESS (in. H2O)	0.6	0.6	0.6	0.6	1	1	1	1	1
BOOST (volts)	1.67	1.67	1.67	1.673	1.802	1.802	1.8	1.8	1.8
BOOST (psi)	2.16	2.16	2.16	2.19	3.48	3.48	3.46	3.46	3.46
IN MANIFOLD AIR TEMP (c)	52	50	50	50	61	63	63	64	63
EXHAUST BACK PRESS (psi)	1	1	1	1	2.3	2.2	2.2	2	2.1
EXHAUST TEMP (c)	312	306	312	314	458	428	417	373	376
COOLANT IN TEMP (c)	50	47	51	50	49	45	46	46	47
COOLANT OUT TEMP (c)	56	53	57	56	59	56	57	57	58
OIL PRESS (psi)	43.2	42.9	41	41	34.3	31.9	29.6	33.7	32.5
OIL TEMP (c)	72	72	75	75	82	90	97	102	105
AMB. TEMP (c)	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
WET BULB TEMP	10.5	10.5	10.5	10.5	11.0	11.0	11.0	11.0	10.5
ATM. PRESS (in Hg)	29.94	29.94	29.94	29.94	29.85	29.85	29.85	29.85	29.94

* means stable operation

TEST #5 **DME SUBSTITUTION TEST MAP NO GLOW PLUG**

DATE	DEC 7/89 2 PM		DEC 12/89 2 PM					
	21	22	23	24	25	26	27	28
SPEED (rpm)	1300	1300	1300	1300	1900	1900	1900	1900
TORQUE (ftlbf)	53	53	53	53	37	35.8	35.5	35.5
	*	*	*	*	*	*	*	*
% FULL LOAD @ THIS SPEED	50%	50%	50%	50%	50%	50%	50%	50%
BRAKE HP (raw)	13.1	13.1	13.1	13.1	13.4	13.0	12.8	12.8
BSFC (lbm/HP hr)	1.016	1.024	0.977	0.903	1.318	1.304	1.279	1.236
EFFICENCY	28.1	27.5	27.6	27.6	21.9	21.8	21.5	21.0
DME % ENERGY	3	5	9	16	3	4	7	12
DME % MASS	2	4	6	12	2	3	5	9
PHI DME	0.01	0.02	0.04	0.07	0.01	0.01	0.03	0.05
PHI METHANOL	0.40	0.40	0.39	0.36	0.38	0.35	0.35	0.34
PHI COMBINED	0.41	0.43	0.43	0.43	0.39	0.37	0.37	0.38
PEAK PRESSURE (psi)	1190	1204	1212	1260	1052	979	1083	1108
PEAK PRESS. AT (deg ATDC	11	12	11	10	13	13	8	7
dP/dt (psi/deg)	68	56	38	48	49	46	50	41
IGNITION DELAY (deg)	8	8	7	6	12	13	10	7
FUEL FLOW (gm/s)	1.68	1.69	1.62	1.49	2.22	2.13	2.07	2.00
FUEL IN PRESS (read)	19	19	18.1	16.8	25.5	24.4	23.4	22.4
FUEL IN PRESS (psi)	47.5	47.5	45.25	42	63.75	61	58.5	56
FUEL OUT TEMP (c)	48	48	49	60	54	53	54	54
DME FLOW (volts)	0.36	0.51	0.85	1.51	0.37	0.52	0.86	1.5
DME MASSFLOW (g/s)	0.041	0.062	0.107	0.196	0.043	0.063	0.109	0.195
DME PRESSURE (KPa)	354	352	353	347	329	323	320	323
AIR FLOW (cfm)	47.1	46.8	46.3	46.2	66.2	67.5	66.8	66.3
AIR FLOW (gm/s)	27.2	27.1	26.8	26.7	38.3	39.0	38.6	38.3
IN. AIR PRESS (in. H2O)	0.9	0.9	0.9	0.9	1.3	1.3	1.3	1.3
BOOST (volts)	1.94	1.94	1.94	1.94	2.1	2.11	2.11	2.11
BOOST (psi)	4.86	4.86	4.86	4.86	6.46	6.56	6.56	6.56
IN MANIFOLD AIR TEMP (c)	57	61	64	64	78	68	73	76
EXHAUST BACK PRESS (psi)	2.2	2.2	2.2	2.2	3	3	3	2.96
EXHAUST TEMP (c)	376	384	387	395	410	399	400	407
COOLANT IN TEMP (c)	46	48	48	48	46	45	46	46
COOLANT OUT TEMP (c)	55	56	57	57	58	57	58	58
OIL PRESS (psi)	41.5	41.5	41.5	41.5	31.1	30.9	31	30.9
OIL TEMP (c)	74	74	74	74	81	82	82	82
AMB. TEMP (c)	23.5	23.5	23.5	23.5	20.5	20.5	20.5	20.5
WET BULB TEMP	10.5	10.5	10.5	10.5	10.0	10.0	10.0	10.0
ATM. PRESS (in Hg)	29.94	29.94	29.94	29.94	29.58	29.58	29.58	29.58

* means stable operation

TEST #5

DME SUBSTITUTION TEST MAP NO GLOW PLUG

DATE	DEC 7/89 2 PM				DEC 12/89 2 PM			
	29	30	31	32	33	34	35	36
SPEED (rpm)	1300	1300	1300	1300	1900	1900	1900	1900
TORQUE (ftlbf)	79.2	78	78	78.2	54	54.8	54	53.7
	*	*	*	*	*	*	*	*
% FULL LOAD @ THIS SPEED	75%	75%	75%	75%	75%	75%	75%	75%
BRAKE HP (raw)	19.6	19.3	19.3	19.4	19.5	19.8	19.5	19.4
BSFC (lbm/HP hr)	0.910	0.907	0.856	0.820	1.213	1.187	1.120	1.075
EFFICENCY	31.7	31.4	32.2	31.6	24.0	23.7	24.0	24.1
DME % ENERGY	3	4	7	12	2	5	9	13
DME % MASS	2	3	5	9	1	3	7	9
PHI DME	0.01	0.02	0.03	0.05	0.01	0.02	0.04	0.05
PHI METHANOL	0.41	0.41	0.39	0.38	0.42	0.43	0.40	0.39
PHI COMBINED	0.42	0.43	0.42	0.43	0.43	0.45	0.44	0.44
PEAK PRESSURE (psi)	1666	1666	1701	1743	1392	1408	1426	1440
PEAK PRESS. AT (deg ATDC	8	8	8	7	5	7	6	6
dP/dt (psi/deg)	106	90	65	50	102	56	49	53
IGNITION DELAY (deg)	8	7	5	4	10	7	5	0
FUEL FLOW (gm/s)	2.25	2.21	2.08	2.00	2.99	2.97	2.76	2.63
FUEL IN PRESS (read)	30.7	29	28	27	41.8	39.5	37.3	34.8
FUEL IN PRESS (psi)	76.75	72.5	70	67.5	104.5	98.75	93.25	87
FUEL OUT TEMP (c)	42	48	50	51	48	52	55	58
DME FLOW (volts)	0.36	0.51	0.85	1.52	0.34	0.85	1.5	2
DME MASSFLOW (g/s)	0.041	0.062	0.107	0.198	0.039	0.107	0.195	0.262
DME PRESSURE (KPa)	356	350	343	342	333	331	331	331
AIR FLOW (cfm)	61.0	59.6	59.2	58.9	78.7	77.5	77.0	76.4
AIR FLOW (gm/s)	35.3	34.5	34.2	34.1	45.5	44.8	44.5	44.2
IN. AIR PRESS (in. H2O)	1.2	1.2	1.2	1.2	1.8	1.8	1.8	1.8
BOOST (volts)	2.46	2.451	2.443	2.44	2.48	2.46	2.46	2.455
BOOST (psi)	10.06	9.97	9.89	9.86	10.26	10.06	10.06	10.01
IN MANIFOLD AIR TEMP (c)	59	84	88	88	81	89	92	95
EXHAUST BACK PRESS (psi)	3.6	3.4	3.4	3.4	6.2	6.2	6.2	6.2
EXHAUST TEMP (c)	410	417	422	434	459	465	470	474
COOLANT IN TEMP (c)	48	47	47	47	46	45	44	45
COOLANT OUT TEMP (c)	56	58	58	59	60	60	60	60
OIL PRESS (psi)	45	37	34	33	30	27	34.9	96
OIL TEMP (c)	68	86	91	95	84	96	102	37
AMB. TEMP (c)	23.5	23.5	23.5	23.5	20.5	20.5	20.5	20.5
WET BULB TEMP	10.5	10.5	10.5	10.5	10.0	10.0	10.0	10.0
ATM. PRESS (in Hg)	29.94	29.94	29.94	29.94	29.58	29.58	29.58	29.58

* means stable operation

TEST #5 **DME SUBSTITUTION TEST MAP NO GLOW PLUG**

DATE	DEC 13/89							
	37	38	39	40	41	42	43	44
SPEED (rpm)	1300	1300	1300	1300	1900	1900	1900	1900
TORQUE (ftlbf)	103.5 *	103.5 *	103.4 *	102.8 *	71.8 *	72 *	73.6 *	72 *
% FULL LOAD @ THIS SPEED	100%	100%	100%	100%	100%	100%	100%	100%
BRAKE HP (raw)	25.6	25.6	25.6	25.4	26.0	26.0	26.6	26.0
BSFC (lbm/HP hr)	0.929	0.894	0.878	0.843	1.091	1.103	1.084	1.051
EFFICENCY	31.2	32.1	32.0	31.8	26.7	26.2	26.2	26.0
DME % ENERGY	2	3	5	9	2	2	4	8
DME % MASS	1	2	4	7	1	2	3	5
PHI DME	0.01	0.01	0.02	0.03	0.01	0.01	0.02	0.04
PHI METHANOL	0.38	0.36	0.36	0.35	0.46	0.47	0.47	0.45
PHI COMBINED	0.39	0.38	0.38	0.38	0.47	0.48	0.49	0.49
PEAK PRESSURE (psi)	2067	2057	2096	2135	1718	1730	1750	1774
PEAK PRESS. AT (deg ATDC	5	5	5	5	7	6	5	7
dP/dt (psi/deg)	184	148	128	89	119	107	89	62
IGNITION DELAY (deg)	7	5	4	0	8	7	6	3
FUEL FLOW (gm/s)	3.00	2.88	2.83	2.70	3.57	3.62	3.64	3.45
FUEL IN PRESS (read)	45.9	45.6	44.3	42.2	63	63.8	64.3	59.5
FUEL IN PRESS (psi)	114.75	114	110.75	105.5	157.5	159.5	160.75	148.75
FUEL OUT TEMP (c)	50	48	48	49	55	55	56	56
DME FLOW (volts)	0.36	0.51	0.85	1.51	0.35	0.5	0.84	1.51
DME MASSFLOW (g/s)	0.041	0.062	0.107	0.196	0.040	0.060	0.106	0.196
DME PRESSURE (KPa)	326	322	319	327	327	320	320	319
AIR FLOW (cfm)	88.6	88.5	88.1	87.6	86.5	86.2	85.9	85.7
AIR FLOW (gm/s)	51.2	51.2	51.0	50.7	50.0	49.9	49.7	49.6
IN. AIR PRESS (in. H2O)	2.2	2.2	2.2	2.2	2.1	2.1	2.1	2.1
BOOST (volts)	2.7	2.72	2.72	2.72	2.76	2.75	2.75	2.75
BOOST (psi)	12.46	12.66	12.66	12.66	13.06	12.96	12.96	12.96
IN MANIFOLD AIR TEMP (c)	68	78	84	87	100	106	108	108
EXHAUST BACK PRESS (psi)	6.2	6.1	6	5.9	8.8	8.7	8.8	8.7
EXHAUST TEMP (c)	485	497	506	508	520	530	537	534
COOLANT IN TEMP (c)	41	44	45	45	43	43	43	43
COOLANT OUT TEMP (c)	55	58	59	59	61	61	61	61
OIL PRESS (psi)	50.5	48.9	47.7	47	37	37.5	37.7	37.8
OIL TEMP (c)	78	81	83	84	95	94	94	93
AMB. TEMP (c)	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
WET BULB TEMP	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATM. PRESS (in Hg)	29.58	29.58	29.58	29.58	29.58	29.58	29.58	29.58

* means stable operation

NOTES ON METHANOL SINGLE CYLINDER ENGINE TESTS

TEST #6

DECEMBER 19, 1989
DME SUBSTITUTION TEST MAP NO GLOW PLUG
WITH EMISSIONS

This test was to determine the emissions trends with varying percentages of DME substitution. The timing was kept constant at .130 inch static injection timing. This timing yields a range of beginning of injection marks from 8 degrees ATDC at idle to 12 degrees BTDC at full load. End of injection remains almost constant at 28 degrees ATDC.

The emissions calculations have been corrected for the molecular weight of methanol and DME. The correction for molecular weight was done on a fractionally weighted basis. The molecular weight used was a weighted average of methanol and DME. The weighting was determined by the percentage of DME admitted to the engine. This assumes the unburned hydrocarbons in the exhaust will be in the same ratio as the fuel input, (not very likely). This assumption will be tested and if needs be corrected when the gas chromatograph results are analysed. The lower heating value of methanol (20,000 kJ/kg), and DME (28,800 kJ/kg) were used for efficiency rates. The hydrocarbon readings have not been adjusted for the sensitivity factor of the FID to methanol or DME. Emissions calculations were done on a dry basis. Air flow values have
not been corrected for ambient pressure variations.

It should be noted that these results are from steady state tests on a single cylinder engine. The high friction of the engine results in skewed values and therefore this data should not be compared with other engine results. The tests should be viewed on a strictly comparative basis.

TEST #6 — DME SUBSTITUTION TEST MAP NO GLOW PLUG

DATE: DEC 19/89 2:PM

	1	2	3	4	5	6	7	8	9
SPEED (rpm)	820	1300	1300	1320	1300	1300	1300	1300	1300
TORQUE (ftlbf)	2.2	2.6	2.4	2.4	32.5	27.8	27.6	51	52.2
% FULL LOAD @ THIS SPEED	IDLE	2%	2%	2%	25%	25%	25%	50%	50%
BRAKE HP (raw)	0.3	0.6	0.6	0.6	8.0	6.9	6.8	12.6	12.9
BSFC (lbm/HP hr)	0.065	10.923	0.833	9.026	1.207	1.277	1.362	1.141	1.079
EFFICIENCY	3.3	2.5	3.0	2.9	24.8	22.2	20.5	25.7	27.0
DME % ENERGY	32	21	31	36	7	13	22	3	5
DME % MASS	25	15	24	28	5	10	17	2	4
PHI DME	0.06	0.07	0.08	0.09	0.02	0.04	0.08	0.01	0.02
PHI METHANOL	0.13	0.26	0.17	0.17	0.33	0.29	0.28	0.41	0.40
PHI COMBINED	0.19	0.32	0.25	0.26	0.35	0.33	0.35	0.43	0.42
FUEL FLOW (gm/s)	0.26	0.75	0.50	0.50	1.16	1.00	0.96	1.77	1.69
FUEL IN PRESS (read)	2.7	6.1	3.9	3.9	9.8	8.4	7.5	19.2	18.6
FUEL IN PRESS (psi)	6.75	15.25	9.75	9.75	24.5	21	18.75	48	46.5
FUEL OUT TEMP (c)	51	51	55	53	47	50	50	45	45
DME FLOW (volts)	0.7	1.06	1.23	1.47	0.5	0.85	1.49	0.36	0.51
DME MASSFLOW (g/s)	0.087	0.136	0.159	0.191	0.060	0.107	0.194	0.041	0.062
DME PRESSURE (KPa)	312	328	329	330	311	311	311	325	317
AIR FLOW (cfm)	22.0	32.4	32.5	33.2	39.6	39.0	38.8	47.8	47.8
AIR FLOW (gm/s)	12.7	18.7	18.8	19.2	22.9	22.6	22.4	27.6	27.6
IN. AIR PRESS (in. H2O)	0.3	0.5	0.5	0.5	0.6	0.6	0.6	0.8	0.8
BOOST (volts)	1.52	1.5	1.5	1.5	1.67	1.67	1.67	1.95	1.95
BOOST (psi)	0.66	0.46	0.46	0.46	2.16	2.16	2.16	4.96	4.96
IN MANIFOLD AIR TEMP (c)	39	42	45	47	47	48	49	50	59
EXHAUST BACK PRESS (psi)	0.29	0.48	0.78	0.8	0.99	0.96	0.96	2.26	2.28
EXHAUST TEMP (c)	144	193	216	220	311	297	301	365	369
COOLANT IN TEMP (c)	51	52	53	51	52	47	49	50	44
COOLANT OUT TEMP (c)	53	56	57	55	57	54	55	59	53
OIL PRESS (psi)	48.8	40	40	41	40	40.3	40.1	39	39
OIL TEMP (c)	66	77	73	74	76	75	76	77	77

INJECTOR/CAM:9-10-250/F1419

PRESS. TRANS:380 PSI/VOLT WET BUL 8.0 DRY BUL 17.5 ATM PRE 29.74

gm H2O/Kg AIR (.1429xgrains 2.57

PART. PRES. H20 IN AIR (inH 0.129 H20 P. SAT.(KP 1.0702

H20 VOL. CONC. IN INTAKE AI 0.004 INT. CONSTANT .0.0003

F/A (stoich) 0.155

H/C RATIO DME 3 FUEL MOL. WEIGH 32.04 METH. 46.07 DME

WATER-GAS EQU. CONSTANT 3.5

	1	2	3	4	5	6	7	8	9
EXHAUST (Kg/min)	0.78	1.17	1.16	1.18	1.44	1.41	1.40	1.77	1.76
F/A (dry)	0.021	0.040	0.027	0.026	0.051	0.044	0.043	0.064	0.061
PHI	0.195	0.324	0.249	0.256	0.352	0.330	0.355	0.428	0.417
SPECIES WET (ppm)									
NOx	92	115	106	118	266	221	237	384	406
THC	350	6000	456	451	720	286	306	115	121
WET to DRY C.F.	1.037	1.045	1.048	1.050	1.079	1.074	1.078	1.094	1.092
SPECIES DRY (ppm carbon)									
CO	4950	4600	4650	5250	718	1417	2162	301	408
CO2%	2.05	2.7	2.8	2.88	5.57	5.03	5.21	6.84	6.66
NOx	96	133	115	127	339	270	288	538	558
THC	363	6272	478	474	777	387	330	126	132
MASS FLOW (gm/hr)									
CO	140.01	268.57	200.81	211.11	44.95	82.20	111.61	24.15	31.91
CO2	938	2477	1900	1820	5480	4585	6226	8625	8186
NOx	5	13	8	8	35	26	26	71	72
THC	13	447	26	24	57	21	21	12	12
BS EMMISIONS (gm/hp.hr)									
CO	407.6	417.3	338.0	350.0	5.6	11.9	16.3	1.9	2.5
CO2	2707.5	3849.2	3198.6	3017.0	681.2	666.3	618.7	683.2	633.6
NOx	13.2	19.9	13.7	14.0	4.3	3.7	3.6	5.6	5.6
THC	38.7	694.8	43.9	40.5	7.1	3.1	3.1	0.9	0.9
MASS SPECIFIC (g/Kg)									
CO	148.57	99.47	111.00	110.46	10.74	22.83	32.24	3.78	5.23
CO2	987	917	1050	1021	1309	1274	1221	1351	1342
NOx	4.81	4.74	4.50	4.72	8.32	7.14	7.06	11.12	11.75
THC	14.12	165.61	14.43	13.72	13.58	5.90	6.04	1.83	1.97

TEST #6

DME SUBSTITUTION TEST MAP NO GLOW PLUG

DATE DEC 19/89 2:PM

	10	11	12	13	14	15	16	17	18	19
SPEED (rpm)	1300	1300	1300	1300	843	1900	1900	1900	1900	1900
TORQUE (ftlbf)	77.6	78	104.4	104.6	2.6	2.6	2.4	2.6	19	18.5
% FULL LOAD @ THIS SPEED	75%	75%	100%	100%	IDLE	2%	2%	2%	25%	25%
BRAKE HP (raw)	19.2	19.3	25.8	25.9	0.4	0.9	0.9	0.9	6.9	6.7
BSFC (lbm/HP hr)	0.929	0.953	0.950	0.937	5.052	10.337	11.231	9.907	1.938	1.953
EFFICENCY	31.6	30.7	31.0	31.3	4.4	2.7	2.4	2.7	14.5	14.1
DME % ENERGY	3	4	2	3	80	23	25	30	16	22
DME % MASS	2	3	1	2	73	17	19	23	12	16
PHI DME	0.01	0.02	0.01	0.01	0.15	0.07	0.08	0.09	0.06	0.08
PHI METHANOL	0.41	0.42	0.51	0.51	0.04	0.25	0.25	0.22	0.30	0.28
PHI COMBINED	0.42	0.44	0.52	0.52	0.18	0.32	0.32	0.31	0.36	0.36
FUEL FLOW (gm/s)	2.21	2.26	3.05	3.00	0.07	1.02	1.00	0.91	1.48	1.38
FUEL IN PRESS (read)	29.1	29.7	47.7	47.3	3.2	8.6	8	7.7	13.7	13
FUEL IN PRESS (psi)	72.75	74.25	119.25	118.25	8	21.5	20	19.25	34.25	32.5
FUEL OUT TEMP (c)	43	45	44	44	59	55	56	56	54	55
DME FLOW (volts)	0.37	0.5	0.35	0.48	1.5	1.61	1.75	2.02	1.5	2.04
DME MASSFLOW (g/s)	0.043	0.060	0.040	0.058	0.195	0.210	0.229	0.265	0.195	0.268
DME PRESSURE (KPa)	316	311	310	310	319	315	312	310	314	309
AIR FLOW (cfm)	60.7	59.8	67.0	66.4	20.7	45.3	45.5	45.7	54.9	54.9
AIR FLOW (gm/s)	35.1	34.6	38.7	38.4	12.0	26.2	26.3	26.4	31.8	31.8
IN. AIR PRESS (in. H2O)	1.1	1.1	1.4	1.4	0.2	0.8	0.8	0.8	0.9	0.9
BOOST (volts)	2.43	2.448	2.76	2.758	1.51	1.58	1.58	1.58	1.815	1.816
BOOST (psi)	9.76	9.94	13.06	13.04	0.56	1.26	1.26	1.26	3.61	3.62
IN MANIFOLD AIR TEMP (c)	76	90	96	99	72	63	60	58	59	62
EXHAUST BACK PRESS (psi)	3.36	3.46	6.2	6.14	0.15	0.8	0.8	0.8	2	1.98
EXHAUST TEMP (c)	403	412	516	519	169	305	298	298	362	361
COOLANT IN TEMP (c)	46	48	43	43	49	43	49	48	48	49
COOLANT OUT TEMP (c)	56	59	58	58	53	52	58	55	57	58
OIL PRESS (psi)	37.8	39	38	37	42	34	33	34	33	33
OIL TEMP (c)	80	75	77	79	75	82	85	83	83	84

INJECTOR/CAM:9-10-250/F1419

PRESS. TRANS:380 PSI/VOLT

gm H2O/Kg AIR (.1429xgrains	2.57		
PART. PRES. H2O IN AIR (inH	0.129	H2O P. SAT.(KP	1.0702
H2O VOL. CONC. IN INTAKE AI	0.004	INT. CONSTANT	0.0003
F/A (stoich)	0.155		
H/C RATIO	4	FUEL MOL. WEIGH	32.04
WATER-GAS EQU. CONSTANT	3.5		

	10	11	12	13	14	15	16	17	18	19
EXHAUST (Kg/min)	2.24	2.21	2.51	2.48	0.72	1.63	1.64	1.64	1.99	1.99
F/A (dry)	0.063	0.065	0.079	0.078	0.006	0.039	0.038	0.034	0.047	0.043
PHI	0.418	0.438	0.519	0.519	0.184	0.323	0.324	0.313	0.358	0.357
SPECIES WET (ppm)										
NOx	NA.	NA.	NA.	NA.	NA.	NA.	NA.	NA.	NA.	NA.
THC	98	98	109	101	465	390	427	474	475	312
WET to DRY C.F.	1.095	1.095	1.116	1.117	1.043	1.065	1.063	1.065	1.073	1.068
SPECIES DRY (ppm carbon)										
CO	184	231	219	218	2226	3600	3900	4300	1823	2335
CO2%	6.92	6.93	8.67	8.77	2.28	4.15	3.98	4.03	4.92	4.67
NOx	720	734	886	910	17	93	86	82	154	150
THC	107	107	122	113	485	415	454	505	510	333
MASS FLOW (gm/hr)										
CO	2.16	7.74	3.96	3.83	241.56	231.48	247.06	483.95	179.50	205.24
CO2	1278	3648	2461	2418	3888	4193	3962	7127	7613	6451
NOx	14	40	26	26	3	10	9	15	25	22
THC	1	4	3	2	80	33	36	71	60	34
BS EMMISIONS (gm/hp.hr)										
CO	0.1	0.4	0.2	0.1	578.8	246.1	284.6	514.5	26.1	30.7
CO2	66.5	189.0	95.2	93.4	9316.6	4458.0	4563.3	7577.5	1107.6	963.8
NOx	0.7	2.1	1.0	1.0	7.3	10.4	10.3	16.1	3.6	3.2
THC	0.1	0.2	0.1	0.1	190.8	34.9	41.0	76.0	8.8	5.0
MASS SPECIFIC (g/Kg)										
CO	0.27	0.95	0.36	0.35	949.47	63.33	68.63	147.87	33.60	41.33
CO2	161	449	224	224	15282	1147	1101	2178	1425	1299
NOx	1.75	4.97	2.39	2.43	11.91	2.69	2.49	4.63	4.66	4.36
THC	0.18	0.51	0.23	0.21	312.94	8.99	9.89	21.83	11.30	6.75

TEST #6 — DME SUBSTITUTION TEST MAP NO GLOW PLUG

DATE	DEC 19/89 2:PM			
	20	21	22	23
SPEED (rpm)	1900	1900	1900	820
TORQUE (ftlbf)	37.8	54.2	71.6	3
% FULL LOAD @ THIS SPEED	50%	75%	100%	IDLE
BRAKE HP (raw)	13.7	19.6	25.9	0.5
BSFC (lbm/HP hr)	1.416	1.233	1.122	5.641
EFFICENCY	20.7	23.9	26.3	4.2
DME % ENERGY	2	2	2	67
DME % MASS	2	1	1	59
PHI DME	0.01	0.01	0.01	0.15
PHI METHANOL	0.40	0.44	0.46	0.07
PHI COMBINED	0.41	0.44	0.47	0.22
FUEL FLOW (gm/s)	2.46	3.01	3.62	0.14
FUEL IN PRESS (read)	26.4	40.8	62.4	3.2
FUEL IN PRESS (psi)	66	102	156	8
FUEL OUT TEMP (c)	51	51	51	61
DME FLOW (volts)	0.35	0.34	0.34	1.5
DME MASSFLOW (g/s)	0.040	0.039	0.039	0.195
DME PRESSURE (KPa)	310	307	306	311
AIR FLOW (cfm)	67.2	77.2	87.4	20.6
AIR FLOW (gm/s)	30.9	44.6	50.5	11.9
IN. AIR PRESS (in. H2O)	1.4	1.8	2.2	0.2
BOOST (volts)	2.13	2.48	2.79	1.517
BOOST (psi)	6.76	10.26	13.36	0.63
IN MANIFOLD AIR TEMP (c)	71	86	96	65
EXHAUST BACK PRESS (psi)	2.95	6.2	8.8	0.14
EXHAUST TEMP (c)	411	455	502	166
COOLANT IN TEMP (c)	44	46	43	50
COOLANT OUT TEMP (c)	57	61	61	53
OIL PRESS (psi)	32	28	31	44
OIL TEMP (c)	88	101	100	83

INJECTOR/CAM:9-10-250/F1419
PRESS. TRANS:380 PSI/VOLT

gm H2O/Kg AIR (.1429xgrains	2.57		
PART. PRES. H20 IN AIR (inH	0.129	H20 P. SAT.(KP	1.0702
H20 VOL. CONC. IN INTAKE AI	0.004	INT. CONSTANT	0.0003
F/A (stoich)	0.155		
H/C RATIO	4	FUEL MOL. WEIGI	32.04
WATER-GAS EQU. CONSTANT	3.5		

	20	21	22	23
EXHAUST (Kg/min)	2.48	2.86	3.25	0.72
F/A (dry)	0.062	0.067	0.072	0.012
PHI	0.409	0.444	0.471	0.222
SPECIES WET (ppm)				
NOx	NA.	NA.	NA.	NA.
THC	185	98	103	281
WET to DRY C.F.	1.082	1.093	1.102	1.037
SPECIES DRY (ppm carbon)				
CO	465	187	173	1774
CO2%	5.88	6.77	7.55	2.04
NOx	281	418	600	100
THC	200	107	114	291
MASS FLOW (gm/hr)				
CO	6.39	6.45	3.59	97.88
CO2	1271	3671	2464	1769
NOx	6	24	20	9
THC	3	4	3	23
BS EMMISIONS (gm/hp.hr)				
CO	18.6	10.0	6.0	162.3
CO2	3699.0	5704.7	4146.9	2932.3
NOx	18.5	36.8	34.5	15.0
THC	9.2	6.6	4.6	38.3
MASS SPECIFIC (g/Kg)				
CO	6.78	2.39	1.99	54.92
CO2	1348	1360	1362	992
NOx	6.74	8.78	11.31	5.09
THC	3.37	1.57	1.50	12.98

NOTES ON METHANOL SINGLE CYLINDER ENGINE TESTS

TEST #7

DECEMBER 19, 1989
13 MODE WITH DME SUBSTITUTION NO GLOW PLUG

This data was extracted from TEST #6 for comparison against the 13 mode glow plug test #4. The timing was kept constant at .130 inch static injection timing. This timing yields a range of beginning of injection marks from 8 degrees ATDC at idle to 12 degrees BTDC at full load. End of injection remains almost constant at 28 degrees ATDC.

The emissions calculations have been corrected for the molecular weight of methanol and DME. The correction for molecular weight was done on a fractionally weighted basis. The molecular weight used was a weighted average of methanol and DME. The weighting was determined by the percentage of DME admitted to the engine. This assumes the unburned hydrocarbons in the exhaust will be in the same ratio as the fuel input, (not very likely). This assumption will be tested and if needs be corrected when the gas chromatograph results are analysed. The lower heating value of methanol (20,000 kJ/kg), and DME (28,800 kJ/kg) were used for efficiency rates. The hydrocarbon readings have not been adjusted for the sensitivity factor of the FID to methanol or DME. Emissions calculations were done on a dry basis. Air flow values have
not been corrected for ambient pressure variations.

It should be noted that these results are from steady state tests on a single cylinder engine. The high friction of the engine results in skewed values and therefore this data should not be compared with other engine results. The tests should be viewed on a strictly comparative basis.

TEST #7 — METHANOL/DME 13 MODE EMMISIONS RUN

DATE — DEC 19/89

	#1	#2	#3	#4	#5	#6	#7
SPEED (rpm)	820	1300	1300	1300	1300	1300	843
TORQUE (ftlbf)	3	2.4	27.8	51	77.6	104.4	2.6
% FULL LOAD @ THIS SPEED	IDLE	2%	25%	50%	75%	100%	IDLE
BRAKE HP (raw)	0.5	0.6	6.9	12.6	19.2	25.8	0.4
BSFC (lbm/HP hr)	2.337	6.714	1.153	1.115	0.911	0.938	1.344
EFFICENCY	4.2	3.0	22.2	25.7	31.6	31.0	4.4
DME % ENERGY	67	31	13	3	3	2	80
DME % MASS	59	24	10	2	2	1	73
PHI DME	0.15	0.08	0.04	0.01	0.01	0.01	0.15
PHI METHANOL	0.07	0.17	0.29	0.41	0.41	0.51	0.04
PHI COMBINED	0.22	0.25	0.33	0.43	0.42	0.52	0.18
FUEL FLOW (gm/s)	0.14	0.50	1.00	1.77	2.21	3.05	0.07
FUEL IN PRESS (% OF 250 psi)	3.2	3.9	8.4	19.2	29.1	47.7	3.2
FUEL IN PRESS (psi)	8	9.75	21	48	72.75	119.25	8
FUEL OUT TEMP (c)	61	55	50	45	43	44	59
DME (volts)	1.5	1.23	0.85	0.36	0.37	0.35	1.5
DME MASSFLOW (g/s)	0.195	0.159	0.107	0.041	0.043	0.040	0.195
DME SUPPLY PRESS (kPa)	311	329	311	325	316	310	319
AIR FLOW (cfm)	20.6	32.5	39.0	47.8	60.7	67.0	20.7
AIR FLOW (gm/s)	11.9	18.8	22.6	27.6	35.1	38.7	12.0
IN. AIR PRESS (in. H2O)	0.2	0.5	0.6	0.8	1.1	1.4	0.2
BOOST (volts)	1.517	1.5	1.67	1.95	2.43	2.76	1.51
BOOST (psi)	0.63	0.46	2.16	4.96	9.76	13.06	0.56
IN MANIFOLD AIR TEMP (c)	65	45	48	50	76	96	72
EXHAUST BACK PRESS (psi)	0.14	0.78	0.96	2.26	3.36	6.2	0.15
EXHAUST TEMP (c)	166	214	297	365	403	516	169
COOLANT IN TEMP (c)	50	53	47	50	46	43	49
COOLANT OUT TEMP (c)	53	57	54	59	56	58	53
OIL PRESS (psi)	44	40	40.3	39	37.8	38	42
OIL TEMP (c)	83	73	75	77	80	77	75

	#8	#9	#10	#11	#12	#13
SPEED (rpm)	1900	1900	1900	1900	1900	820
TORQUE (ftlbf)	2.4	18.5	37.8	54.2	71.6	3
% FULL LOAD @ THIS SPEED	2%	25%	50%	75%	100%	IDLE
BRAKE HP (raw)	0.9	6.7	13.7	19.6	25.9	0.5
BSFC (lbm/HP hr)	9.141	1.636	1.393	1.217	1.110	2.337
EFFICENCY	2.4	14.1	20.7	23.9	26.3	4.2
DME % ENERGY	25	22	2	2	2	67
DME % MASS	19	16	2	1	1	59
PHI DME	0.08	0.08	0.01	0.01	0.01	0.15
PHI METHANOL	0.25	0.28	0.40	0.44	0.46	0.07
PHI COMBINED	0.32	0.36	0.41	0.44	0.47	0.22
FUEL FLOW (gm/s)	1.00	1.38	2.40	3.01	3.62	0.14
FUEL IN PRESS (% OF 250 psi)	8	13	26.4	40.8	62.4	3.2
FUEL IN PRESS (psi)	20	32.5	66	102	156	8
FUEL OUT TEMP (c)	56	55	51	51	51	61
DME (volts)	1.75	2.04	0.35	0.34	0.34	1.5
DME MASSFLOW (g/s)	0.229	0.268	0.040	0.039	0.039	0.195
DME SUPPLY PRESS (kPa)	312	309	310	307	306	311
AIR FLOW (cfm)	45.5	54.9	67.2	77.2	87.4	20.6
AIR FLOW (gm/s)	26.3	31.8	38.9	44.6	50.5	11.9
IN. AIR PRESS (in. H2O)	0.8	0.9	1.4	1.8	2.2	0.2
BOOST (volts)	1.58	1.816	2.13	2.48	2.79	1.517
BOOST (psi)	1.26	3.62	6.76	10.26	13.36	0.63
IN MANIFOLD AIR TEMP (c)	60	62	71	86	96	65
EXHAUST BACK PRESS (psi)	0.8	1.98	2.95	6.2	8.8	0.14
EXHAUST TEMP (c)	298	361	411	455	502	166
COOLANT IN TEMP (c)	49	49	44	46	43	50
COOLANT OUT TEMP (c)	58	58	57	61	61	53
OIL PRESS (psi)	33	33	32	28	31	44
OIL TEMP (c)	85	84	88	101	100	83

WET BULB 8 DRY BULB 17.5 ATM. PRES 29.74

INJECTOR/CAM: 9-10-250/F1419 PRESS. TRANS: 380 PSI/VOLT

TEST #7 **METHANOL/DME 13 MODE EMMISIONS RUN**

DATE DEC 19/89

gm H2O/Kg AIR (.1429xgrains)	2.57		
PART. PRES. H2O IN AIR (inHg)	0.129	H2O P. SAT.(KPa)	1.070277
H2O VOL. CONC. IN INTAKE AIR	0.004	INT. CONSTANT	0.000370
F/A (stoich)	0.155	DME MOL. WEIGHT	46.07
H/C RATIO DME	3	FUEL MOL. WEIGHT	32.04
WATER-GAS EQU. CONSTANT	3.5		

	#1	#2	#3	#4	#5	#6	#7
EXHAUST (Kg/min)	0.73	1.17	1.42	1.77	2.24	2.51	0.73
F/A (dry)	0.028	0.035	0.049	0.066	0.064	0.080	0.022
PHI	4.508	4.020	3.034	2.334	2.395	1.926	5.423
SPECIES WET (ppm)							
NOx	92	106	221	384	513	556	16
THC	350	456	286	115	98	109	465
WET to DRY C.F.	1.041	1.048	1.074	1.094	1.095	1.116	1.043
SPECIES DRY (ppm carbon)							
CO	4850	4650	1417	301	184	219	2226
CO2%	2.05	2.8	5.03	6.84	6.92	8.67	2.28
NOx	100	120	277	544	720	885	17
THC	364	478	307	126	107	122	485
MASS FLOW (gm/hr)							
CO	157.23	264.20	91.03	24.72	18.58	24.35	55.19
CO2%	1044	2500	5078	8827	10979	15148	888
NOx	5	11	29	73	119	162	1
THC	17	34	24	12	12	16	18
BS EMMISIONS (gm/hp.hr)							
CO	335.7	444.7	13.2	2.0	1.0	0.9	132.2
CO2%	2229.6	4208.3	737.9	699.2	571.6	586.2	2128.6
NOx	11.3	18.9	4.3	5.8	6.2	6.3	1.6
THC	36.3	57.8	3.4	0.9	0.7	0.6	43.6
MASS SPECIFIC (g/Kg)							
CO	131.18	111.00	22.83	3.78	2.29	2.19	57.71
CO2%	871.34	1050.35	1273.65	1351.24	1356.22	1360.18	928.81
NOx	4.43	4.71	7.35	11.24	14.75	14.52	0.72
THC	14.17	14.43	5.90	1.83	1.54	1.40	19.02

	#8	#9	#10	#11	#12	#13
EXHAUST (Kg/min)	1.65	2.00	2.48	2.86	3.25	0.73
F/A (dry)	0.047	0.052	0.063	0.068	0.073	0.028
PHI	3.088	2.803	2.446	2.254	2.125	4.508
SPECIES WET (ppm)						
NOx	70	118	203	288	398	93
THC	427	312	185	98	103	281
WET to DRY C.F.	1.061	1.071	1.087	1.100	1.111	1.032
SPECIES DRY (ppm carbon)						
CO	3900	2335	465	187	173	1774
CO2%	3.98	4.67	5.88	6.77	7.55	2.04
NOx	86	150	281	417	599	100
THC	453	334	201	108	114	290
MASS FLOW (gm/hr)						
CO	315.70	228.79	59.60	26.21	26.18	65.83
CO2%	5063	7191	11843	14912	17952	1190
NOx	11	24	59	96	149	6
THC	45	40	30	17	20	15
BS EMMISIONS (gm/hp.hr)						
CO	363.6	34.2	4.4	1.3	1.0	140.5
CO2%	5831.1	1074.4	866.1	760.5	693.1	2539.7
NOx	13.1	3.6	4.3	4.9	5.8	13.0
THC	52.3	6.0	2.2	0.9	0.8	33.0
MASS SPECIFIC (g/Kg)						
CO	71.38	38.59	6.78	2.39	1.99	54.93
CO2%	1144.62	1212.72	1348.19	1359.75	1361.76	992.54
NOx	2.57	4.08	6.73	8.76	11.30	5.08
THC	10.26	6.77	3.38	1.59	1.51	12.91

13 MODE TOTALS

CO	9.86	NOx	5.60
CO2%	767.49	THC	2.20

NOTES ON METHANOL SINGLE CYLINDER ENGINE TESTS

TEST #8

JANUARY 11, 1990
9 MODE METHANOL-GLOWPLUG ALDEHYDE RUN

This test was to determine the aldehyde levels in the exhaust gases when the engine was fueled with methanol only. A portion of the exhaust gases were drawn through a heated line into a single midget impinger containing 20 ml. of 2,4-dinitrophenyl-hydrazine in acetonitrile. These samples where subsequently analysed for aldehyde levels.

The timing was kept constant at .130 inch static injection timing. This timing yields a range of beginning of injection marks from 8 degrees ATDC at idle to 12 degrees BTDC at full load. End of injection remains almost constant at 28 degrees ATDC.

The lower heating value of methanol (20,000 kJ/kg), and DME (28,800 kJ/kg) were used for efficiency rates. Emissions calculations were done on a dry basis. Air flow values have not been corrected for ambient pressure variations.

It should be noted that these results are from steady state tests on a single cylinder engine. The high friction of the engine results in skewed values and therefore this data should not be compared with other engine results. The tests should be viewed on a strictly comparative basis.

TEST #8

DATE

METHANOL-GLOWPLUG 9 MODE ALDYHDE RUN

JAN 11/90

	#1	#2	#3	#4	#5	#6	#7	#8	#9
SPEED (rpm)	800	1330	1300	1300	1300	1900	1900	1900	1900
TORQUE (ftlbf)	0.1	0.1	29	52.2	101.2	3.5	18	35	72
% FULL LOAD @ THIS SPEED	IDLE	2%	25%	50%	100%	2%	25%	50%	100%
BRAKE HP (raw)	0.0	0.0	7.2	12.9	25.0	1.3	6.5	12.7	26.0
BSFC (lbm/HP hr)	NA	NA	1.540	1.147	0.980	NA	2.845	1.429	1.099
EFFICENCY	0.1	0.1	19.2	25.8	30.2	2.8	10.4	20.7	26.9
DME - ENERGY	0	0	0	0	0	0	0	0	0
DME - MASS	0	0	0	0	0	0	0	0	0
PHI DME	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PHI METHANOL	0.27	0.34	0.40	0.42	0.48	0.40	0.51	0.39	0.44
PHI COMBINED	0.27	0.34	0.40	0.42	0.48	0.40	0.51	0.39	0.44
FUEL FLOW (gm/s)	0.59	1.12	1.39	1.87	3.09	1.66	2.33	2.28	3.61
FUEL IN PRESS (% OF 250 psi)	5.1	9.5	12.2	18.2	48.4	17.2	21.2	27.8	67.2
FUEL IN PRESS (psi)	12.75	23.75	30.5	45.5	121	43	53	69.5	168
FUEL OUT TEMP (c)	46	46	49	46	47	56	54	59	53
DME (volts)	0	0	0	0	0	0	0	0	0
DME MASSFLOW (g/s)	0	0	0	0	0	0	0	0	0
DME SUPPLY PRESS (kPa)	0	0	0	0	0	0	0	0	0
AIR FLOW (cfm)	24.2	37.5	38.5	49.2	72.8	46.5	50.8	65.3	91.5
AIR FLOW (gm/s)	14.0	21.7	22.3	28.5	42.1	26.9	29.4	37.8	52.9
IN. AIR PRESS (in. H2O)	0.3	0.4	0.6	0.8	1.5	1	1	1.3	2.3
BOOST (volts)	1.57	1.53	1.67	1.96	2.75	1.59	1.71	2.06	2.71
BOOST (psi)	1.16	0.76	1.602	5.06	12.96	1.36	2.56	6.06	12.56
IN MANIFOLD AIR TEMP (c)	50	50	53	70	103	58	56	72	88
EXHAUST BACK PRESS (psi)	0.18	0.33	1.1	1.85	5.81	1.78	2.38	3	8.7
EXHAUST TEMP (c)	157	224	359	375	520	433	499	432	523
COOLANT IN TEMP (c)	54	47	48	49	45	47	46	47	42
COOLANT OUT TEMP (c)	56	52	55	58	60	57	58	59	58
OIL PRESS (psi)	42	38.2	35	35	31.6	29.6	33.2	31.3	31.8
OIL TEMP (c)	65	68	75	73	82	82	77	82	80
Q1 STORAGE	100	101	102	103	104	105	106	107	108

WET BULB 8 DRY BULB 17.5 ATM. PRE 29.74

INJECTOR/CAM: 9-10-250/F1419

PRESS. TRANS: 380 PSI/VOLT

DATE

METHANOL-GLOWPLUG 9 MODE ALDYHDE RUN

JAN 11/90

	#1	#2	#3	#4	#5	#6	#7	#8	#9
EXHAUST (Kg/min)	0.88	1.37	1.42	1.82	2.71	1.71	1.90	2.40	3.39
FORMALDEHYDE ppm volume	136.00	157.00	58.00	8.00	12.00	264.00	97.00	13.00	12.00
ACETALDEHYDE ppm volume	3.00	5.00	3.00	4.00	3.00	4.00	2.00	1.00	3.00
ALDEHYDE TOTAL ppm volume	139.00	162.00	61.00	12.00	15.00	268.00	99.00	14.00	15.00
FORMALDEHYDE ppm mass	141.00	162.00	60.00	8.00	12.00	274.00	101.00	13.00	12.00
ACETALDEHYDE ppm mass	4.00	7.00	4.00	7.00	5.00	6.00	3.00	2.00	3.00
ALDEHYDE TOTAL ppm mass	145.00	169.00	64.00	15.00	17.00	280.00	104.00	15.00	15.00
FORMALDEHYDE gm/hr	7.41	13.30	5.11	0.87	1.95	28.16	11.53	1.87	2.44
ACETALDEHYDE gm/hr	0.21	0.57	0.34	0.76	0.81	0.62	0.34	0.29	0.61
ALDEHYDE TOTAL gm/hr	7.62	13.88	5.45	1.64	2.77	28.78	11.87	2.16	3.05
FORMALDEHYDE gm/(hp hr)	486.21	525.34	0.71	0.07	0.08	22.24	1.77	0.15	0.09
ACETALDEHYDE gm/(hp hr)	13.79	22.70	0.05	0.06	0.03	0.49	0.05	0.02	0.02
ALDEHYDE TOTAL gm/(hp hr)	500.00	548.04	0.76	0.13	0.11	22.73	1.82	0.17	0.12
FORMALDEHYDE gm/(kg fuel)	3.46	3.29	1.02	0.13	0.18	4.72	1.37	0.23	0.19
ACETALDEHYDE gm/(kg fuel)	0.10	0.14	0.07	0.11	0.07	0.10	0.04	0.04	0.05
ALDEHYDE TOTAL gm/(kg fuel)	3.56	3.43	1.09	0.24	0.25	4.82	1.41	0.26	0.23

NOTES ON METHANOL SINGLE CYLINDER ENGINE TESTS

TEST #9

JANUARY 17, 1990
9 MODE METHANOL/DME ALDEHYDE & GAS CHROMATOGRAPH RUN

This test was to determine the aldehyde levels in the exhaust gases when the engine was fueled with methanol only. A portion of the exhaust gases were drawn through a heated line into a single midget impinger containing 20 ml. of 2,4-dinitrophenyl-hydrazine in acetonitrile. These samples where subsequently analysed for aldehyde levels.

This test was also used to characterize the hydrocarbon emissions with the use of a Gas Chromatograph. The GC was calibrated for Methanol, DME and Methane. The Methane was added after preliminary runs evidenced its presence.

The timing was kept constant at .130 inch static injection timing. This timing yields a range of beginning of injection marks from 8 degrees ATDC at idle to 12 degrees BTDC at full load. End of injection remains almost constant at 28 degrees ATDC.

The lower heating value of methanol (20,000 kJ/kg), and DME (28,800 kJ/kg) were used for efficiency rates. Emissions calculations were done on a dry basis. Air flow values have not been corrected for ambient pressure variations.

It should be noted that these results are from steady state tests on a single cylinder engine. The high friction of the engine results in skewed values and therefore this data should not be compared with other engine results. The tests should be viewed on a strictly comparative basis.

TEST #9 — METHANOL/DME 9 MODE ALDYHDE & GC RUN

DATE	JAN 17/90								
	#1	#2	#3	#4	#5	#6	#7	#8	#9
SPEED (rpm)	775	1300	1300	1306	1300	1906	1901	1900	1900
TORQUE (ftlbf)	0.2	4	26.8	56.6	103.1	2.6	18.8	35.8	70.8
FULL LOAD @ THIS SPEED	IDLE	2%	25%	50%	100%	2%	25%	50%	100%
BRAKE HP (raw)	0.0	1.0	6.6	14.1	25.5	0.9	6.8	13.0	25.6
BSFC (lbm/HP hr)	24.615	4.153	1.139	1.047	0.921	10.867	1.719	1.325	1.090
EFFICENCY	0.3	4.9	19.9	27.4	31.5	2.2	13.6	19.8	26.7
DME % ENERGY	75	31	23	3	2	20	21	11	2
DME % MASS	68	23	18	2	1	15	15	8	1
PHI DME	0.14	0.07	0.08	0.01	0.01	0.07	0.08	0.04	0.01
PHI METHANOL	0.05	0.16	0.27	0.42	0.47	0.30	0.31	0.36	0.44
PHI COMBINED	0.19	0.22	0.35	0.43	0.48	0.37	0.39	0.40	0.44
FUEL FLOW (gm/s)	0.09	0.52	0.95	1.86	2.96	1.29	1.47	2.16	3.52
FUEL IN PRESS (% OF 250 psi)	5.1	9.5	12.2	18.2	48.4	17.2	21.2	27.8	59.8
FUEL IN PRESS (psi)	12.75	23.75	30.5	45.5	121	43	53	69.5	149.5
FUEL OUT TEMP (c)	46	46	49	46	47	56	54	59	53
DME (volts)	1.5	1.23	1.56	0.36	0.34	1.75	2.05	1.5	0.35
DME MASSFLOW (g/s)	0.195	0.159	0.203	0.041	0.039	0.229	0.269	0.195	0.040
DME SUPPLY PRESS (kPa)	312	312	312	312	312	312	309	310	310
AIR FLOW (cfm)	21.6	37.3	39.2	49.6	70.1	48.5	53.6	67.4	90.3
AIR FLOW (gm/s)	12.5	21.6	22.7	28.7	40.5	28.0	31.0	39.0	52.2
MN. AIR PRESS (in. H2O)	0.3	0.5	0.6	0.9	1.5	0.8	0.96	1.3	2.3
BOOST (volts)	1.55	1.58	1.63	1.97	2.73	1.68	1.79	2.13	2.76
BOOST (psi)	0.96	1.26	1.602	5.16	12.76	2.26	3.36	6.76	13.06
IN MANIFOLD AIR TEMP (c)	50	50	53	70	103	58	60	72	88
EXHAUST BACK PRESS (psi)	0.18	0.33	1.1	1.85	5.81	0.8	1.92	3	8.7
EXHAUST TEMP (c)	157	224	359	375	520	295	360	413	523
COOLANT IN TEMP (c)	54	47	48	49	45	49	50	47	42
COOLANT OUT TEMP (c)	56	52	55	58	60	58	58	59	58
OIL PRESS (psi)	42	38.2	35	35	31.6	29.6	33.2	31	32
OIL TEMP (c)	65	68	75	73	82	82	81	82	90
Q1 STORAGE	100	101	102	103	104	106	107	108	109

WET BULB 8 DRY BULB 17.5 ATM. PRE 29.74

INJECTOR/CAM: 9-10-250/F1419
PRESS. TRANS: 380 PSI/VOLT

METHANOL/DME 9 MODE ALDYHDE RUN

DATE	JAN 17/90								
	#1	#2	#3	#4	#5	#6	#7	#8	#9
EXHAUST (Kg/min)	0.77	1.33	1.43	1.83	2.61	1.77	1.96	2.48	3.35
FORMALDEHYDE ppm volume	38.00	41.00	28.00	13.00	19.00	41.00	35.00	28.00	12.00
ACETALDEHYDE ppm volume	1.00	1.00	1.00	2.00	2.00	1.00	1.00	1.00	2.00
ALDEHYDE TOTAL ppm volume	39.00	42.00	29.00	15.00	21.00	42.00	36.00	29.00	14.00
FORMALDEHYDE ppm mass	39.28	43.44	28.94	13.42	19.00	42.17	35.99	28.63	12.47
ACETALDEHYDE ppm mass	0.82	0.98	1.58	2.01	2.29	1.52	1.31	1.42	2.18
ALDEHYDE TOTAL ppm mass	40.09	44.42	30.52	15.44	21.29	43.69	37.30	30.04	14.65
FORMALDEHYDE gm/hr	1.81	3.48	2.48	1.48	2.98	4.49	4.24	4.26	2.50
ACETALDEHYDE gm/hr	0.04	0.08	0.14	0.22	0.36	0.16	0.15	0.21	0.44
ALDEHYDE TOTAL gm/hr	1.84	3.56	2.62	1.70	3.34	4.65	4.40	4.47	2.94
FORMALDEHYDE gm/(hp hr)	61.23	3.51	0.37	0.10	0.12	4.76	0.62	0.33	0.10
ACETALDEHYDE gm/(hp hr)	1.27	0.08	0.02	0.02	0.01	0.17	0.02	0.02	0.02
ALDEHYDE TOTAL gm/(hp hr)	62.50	3.59	0.39	0.12	0.13	4.93	0.65	0.35	0.11
FORMALDEHYDE gm/(kg fuel)	1.75	1.43	0.60	0.22	0.28	0.82	0.68	0.50	0.20
ACETALDEHYDE gm/(kg fuel)	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03
ALDEHYDE TOTAL gm/(kg fuel)	1.79	1.46	0.63	0.25	0.31	0.85	0.70	0.53	0.23